SPIN EFFECTS IN *pN*- and *pd*- ELASTIC and QUASIELASTIC SCATTERING AT ENERGIES OF SPD NICA

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PLAN:

pN- elastic scattering . Data and parametrizations of pp amplitudes <3 GeV, >3 GeV

Glauber theory of pd- elastic scattering at 0.1-3 GeV

Results of Glauber calculations of spin observables pd-elastic scattering at 3-50 GeV/c

Quaslielastic scattering pd-> {pp}(1S0)+n and complete polarization experiment

Spin-dependent pN-amplitudes in search of T-invariance violation in pd-scattering

Conclusion

NN-forces is a basis of nuclear physics .
It is important to study all their components, including spin-dependent terms at low and high energies **via the spin amplitudes of the NN elastic scattering**

PP elastic scattering

Helicity amplitudes of NN-scattering

For identical spin $\frac{1}{2}$ particles under Lorentz and P-,T- invariance:

spin non-flip $\phi_1(s,t) =< ++|M|++>$

double spin-flip $\phi_2(s,t) =< ++|M|-->$

spin non-flip $\phi_3(s,t) =< +-|M|+->$

double spin-flip $\phi_4(s,t) =< +-|M|-+>$

single spin-flip $\phi_5(s,t) =< ++|M|++- >$.

For non-identical (pn) nucleons one has 6 amplitudes,

T-reversal non-invarinace provides two additional amplitudes.

All spin-observables of NN elastic scattering are described in terms of ϕ_i

$$d\sigma/dt = N[|\phi_1|^2 + |\phi_2|^2 + |\phi_1|^3 + |\phi_4|^2 + 4|\phi_5|^2],$$

$$A_N \sim Im[(\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^*]$$

$$A_{NN} \sim 2|\phi_5|^2 + Re(\phi_1^*\phi_2 - \phi_3^*\phi_4)$$

$$\ldots$$

Number of linearly independent non-zero spin observables:
single-spin (asymmetries A_i, polarizations P_i) – 2
double-spin ($A_{ii}, \ldots$) – 12
triple-spin – 9
four- spin – 2

Complete polarization experiment
for pp-elastic requires 9 independent observables.
PWA GWU is performed for pp-elastic up to 3.8 GeV/c (SAID webpage:`http://gwdac.phys.gwu.edu`.
R.A. Arndt, I.I. Strakovsky, B.L. Workman PRC 56, 3005 (1997);
PWA for pn- elastic – up 1.2 GeV/c

Concerning SPD NICA, above 3 GeV/c $d\sigma/dt$ and mainly A_N (up to 50 GeV/c) and A_{NN}, C_{LL} (up to 6 GeV/c, 12 GeV/c) are measured. Data on double-spin observables D_{NN}, K_{NN} are rather poore in the region of forward angles.

Parametrizations (fit) of the pp- data:
Regge: W.P. Ford, J.W. Van Orden, Phy.Rev. **C87** (2013) 014004;
A. Sibirtsev et al. Eur.Phys.J. **A 45** (2010) 357;
Eikonal: S. Wakaizumi, M. Sawamoto,Prog. Theor. Phys. v.64 (1980) 1699

$$\phi_{ai}(s,t) = \pi\beta_{ai}(t)\frac{\xi_i(s,t)}{\Gamma(\alpha(t))};i=\rho,\omega,a_2,f_2,P;a=1-5;$$

$$\xi_i(t,s) = \frac{1+S_i\exp[-i\pi\alpha(t)]}{\sin[\pi\alpha_i(t)]}\left[\frac{s}{s_0}\right]^{\alpha_i(t)},$$

$$\alpha_i(t) = \alpha_i^0 + \alpha_i^{'}t,$$

$$\beta_{1i}(t) = c_{1i}\exp(b_{1i}t),$$

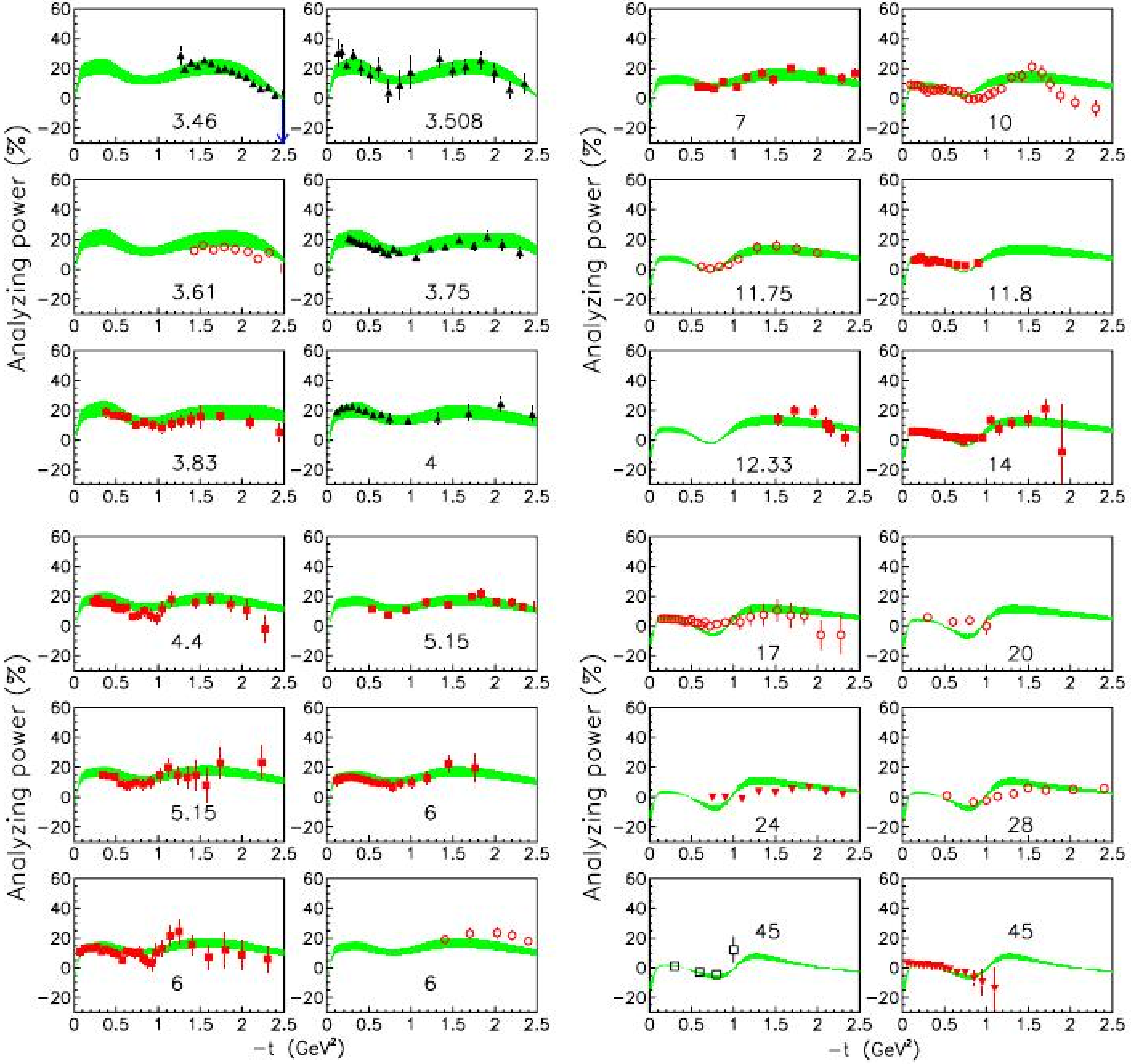
$$\beta_{2i}(t) = c_{2i}\exp(b_{2i}t)\frac{-t}{4m_N^2},$$

$$\beta_{3i}(t) = c_{3i}\exp(b_{3i}t),$$

$$\beta_{4i}(t) = c_{4i}\exp(b_{4i}t)\frac{-t}{4m_N^2},$$

$$\beta_{5i}(t) = c_{5i}\exp(b_{5i}t)\left[\frac{-t}{4m_N^2}\right]^{1/2}.$$

A. Sibirtsev et al, EPJ A 45 (2010)357

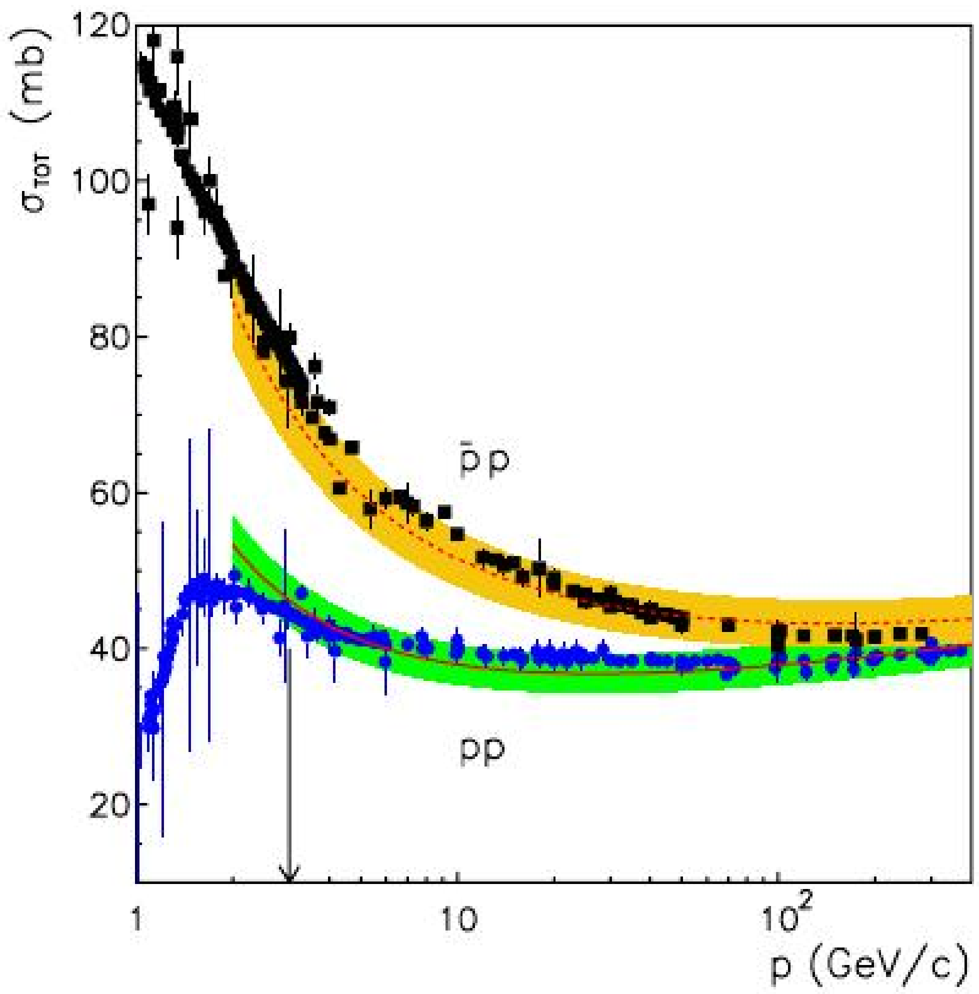


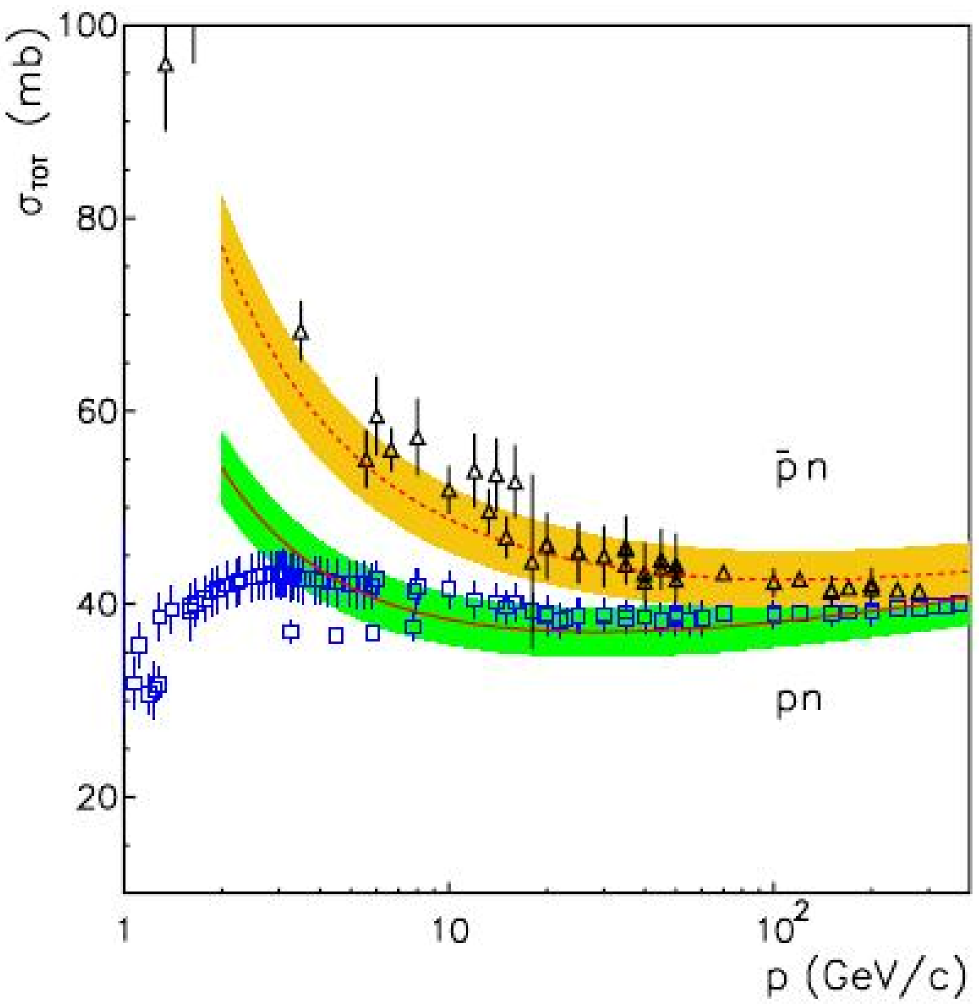
Helicity amplitudes in Regge formalism

A systematic analisys of pp elastic scattering from COSY-EDDA, SATURNE, GZS ANL
A. Sibirtsev, J. Haidenbauer, H.-W. Hammer et al. EPJA 45 (2010) 357
ω, ρ, f_2, a_2 Regge exchanges and the Pomeron for P_L from 3 GeV/c up to 50 GeV/c.
Isospin structure and G-parity relations allow to obtain the $\bar{p}p$-, pn- and $\bar{p}n$ elastic amplitudes from the pp amplitudes (J.R. Pelaez, 2006):

$$\begin{aligned}
\phi(pp) &= -\phi_\omega - \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P \\
\phi(\bar{p}p) &= \phi_\omega + \phi_\rho + \phi_{f_2} + \phi_{a_2} + \phi_P \\
\phi(pn) &= -\phi_\omega + \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P \\
\phi(\bar{p}n) &= \phi_\omega - \phi_\rho + \phi_{f_2} - \phi_{a_2} + \phi_P
\end{aligned}$$

However, not all available data
($C_{NN}, C_{LL}, C_{SS}, C_{LS}, D_{NN}, D_{SS}, D_{LS}, K_{NN}, \Delta\sigma_T, H_{SNS}$... measured by ANL at 6 GeV/c, and some at 12 GeV/c) were included into the fit.





A. Sibirtsev et al, EPJA (2010): full line – pp, dashed – antip p.

PROBLEMS

A. Sibirtsev et al, EPJA (2010)

R- real-to-imaginary part ratio.
A problem with antip-p theory: no zero

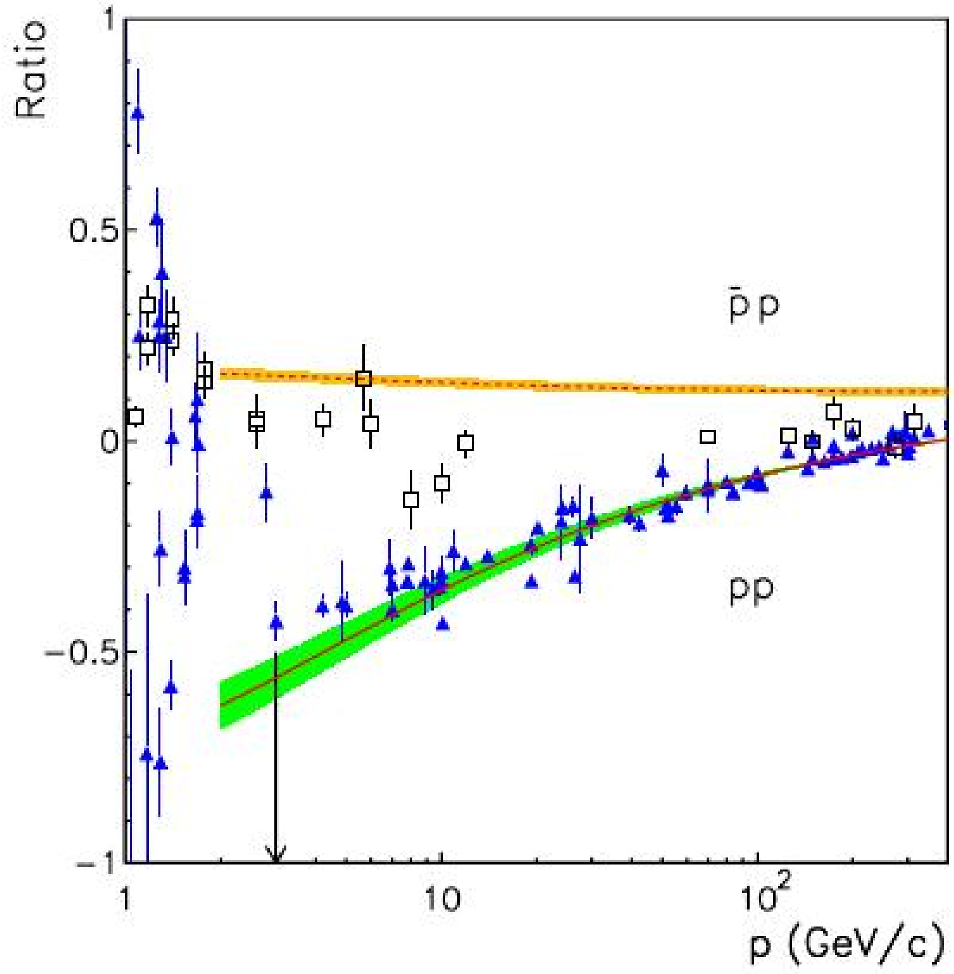
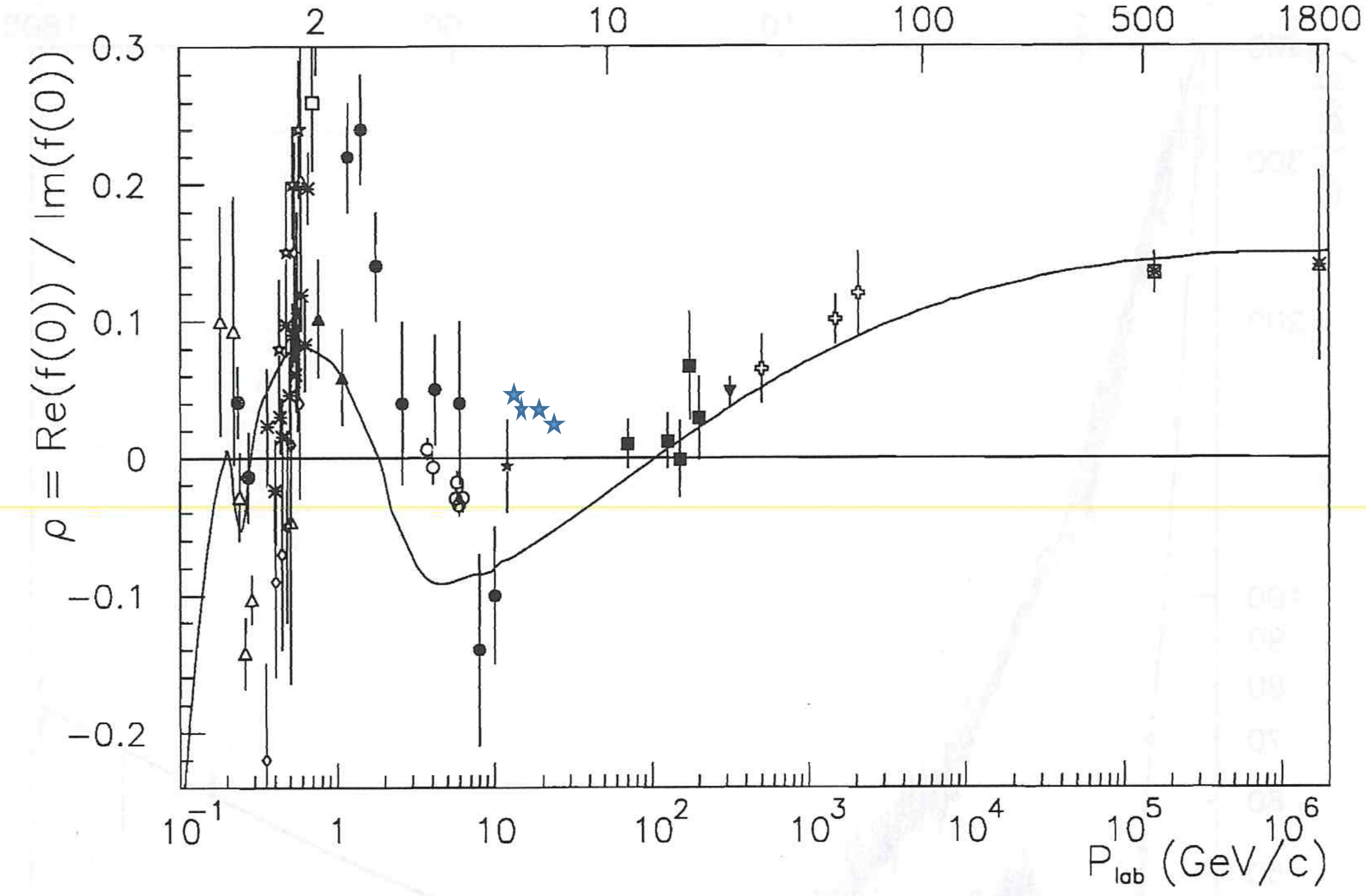


Fig. 16. Ratio of the real-to-imaginary parts of the forward amplitudes for pp (triangles, solid line) and $\bar{p}p$ (squares, dashed line), respectively. The data are taken from the PDG [32].

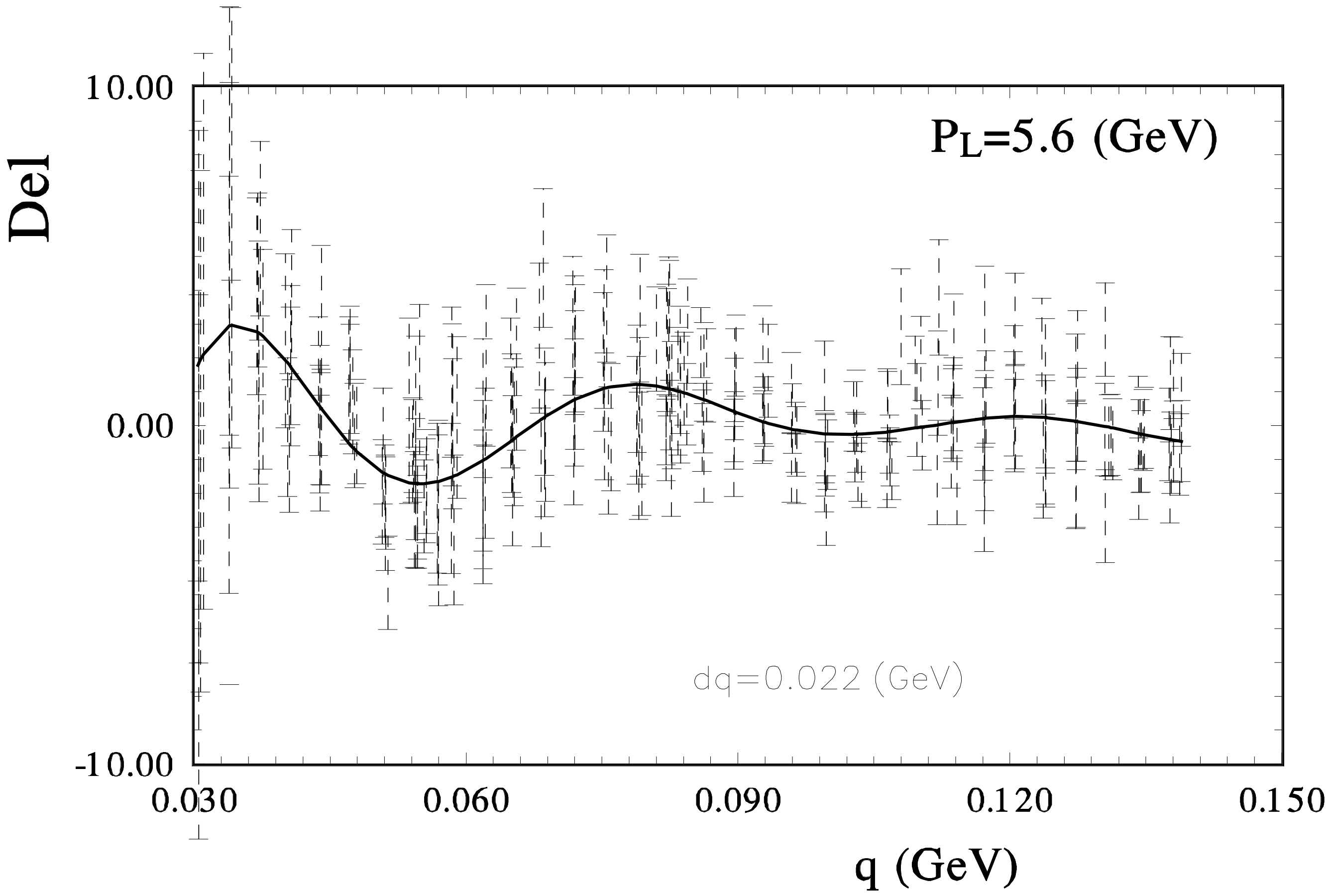
O.V. Selyugin, Mod. Phys. Lett. A 27 (2012) 1250113
A problem with dispersion relations at 5-8 GeV/c .
anti p -p

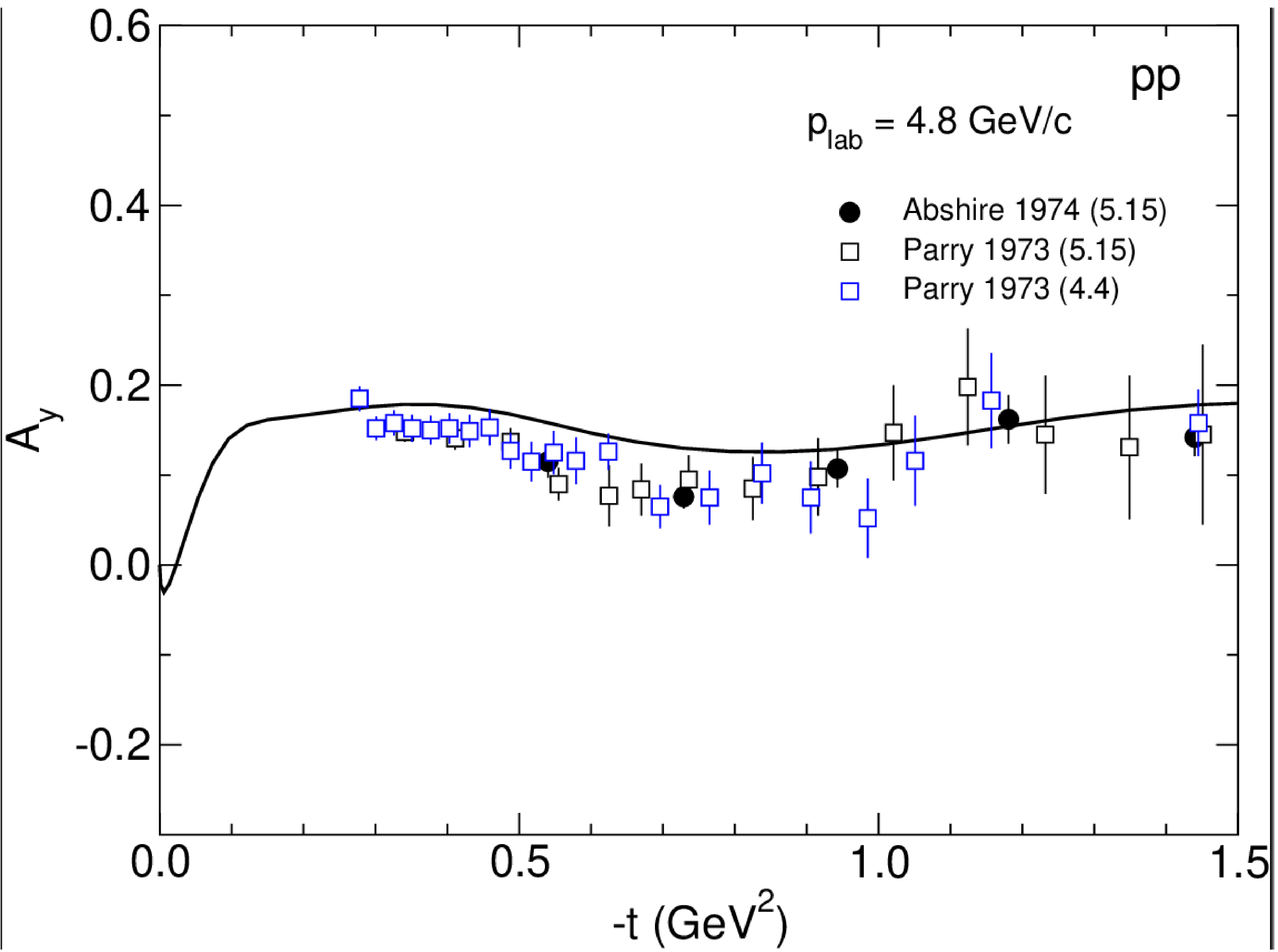


$$Del = \frac{d\sigma/dt_{data.} - d\sigma/dt_{theor-\exp.}}{d\sigma/dt_{theor-\exp.}}$$

P. Gauron, B. Nicolescu, O.V. Selyugin,PLB 397 (1997)

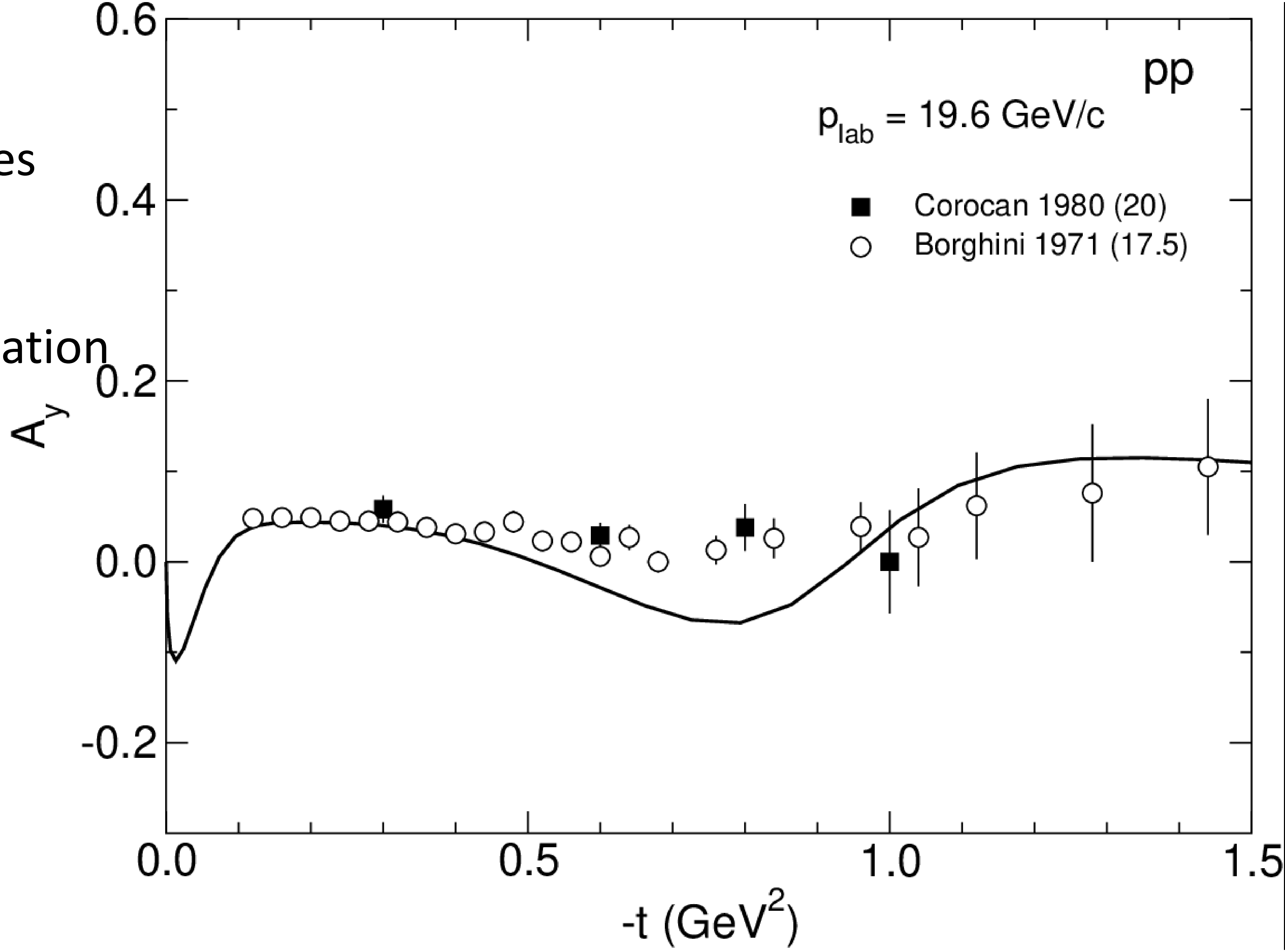
(See talk by A. Ljvov)
Oscillation effect





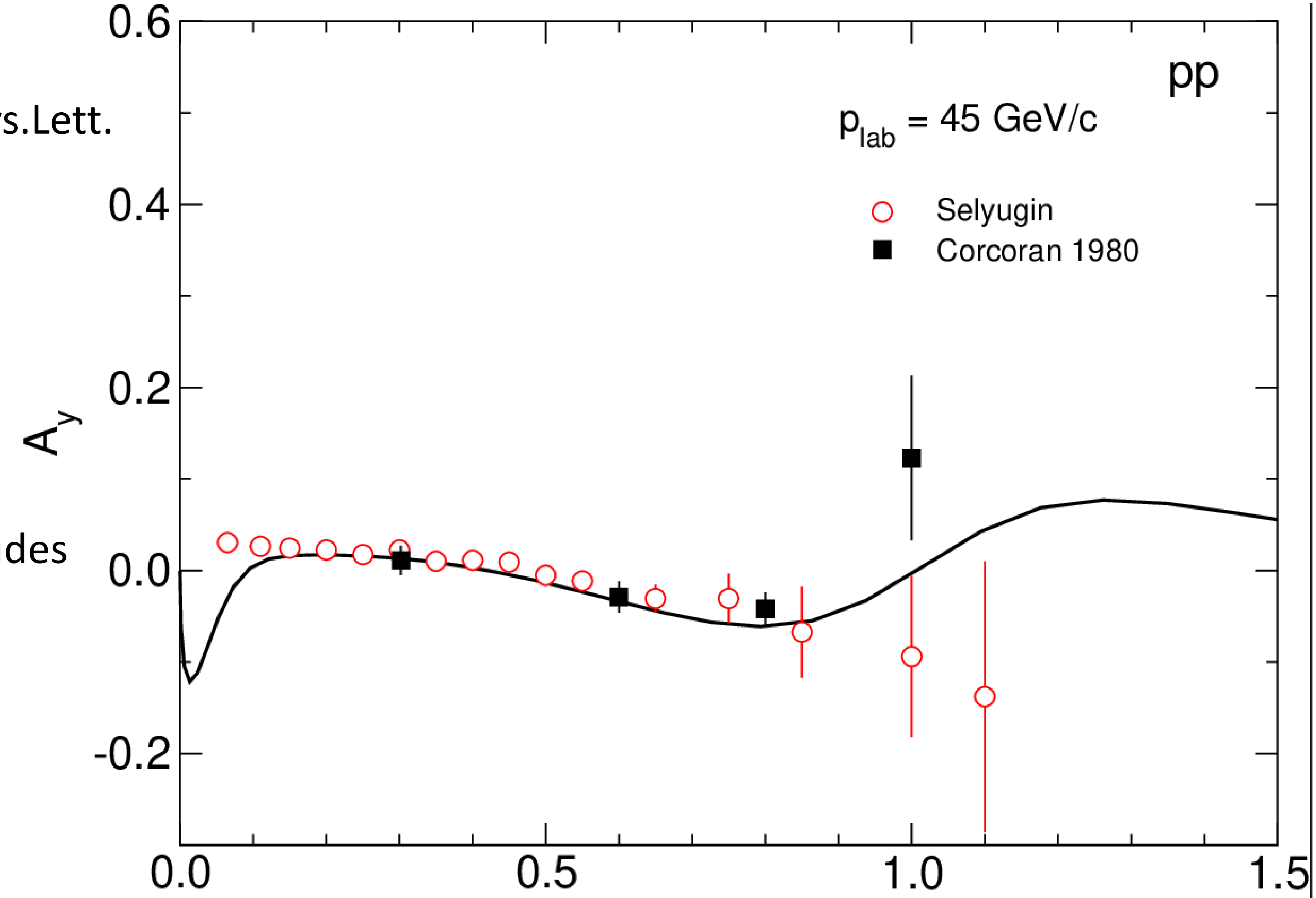
pp- helicity amplitudes A.Sibirtsev Regge parametrization (Gaussian parametrization)

pp- helicity amplitudes
A.Sibirtsev Regge
parametrization
(Gaussian parametrization



https://www.hepdata.net/record/ins113043

A.Gaidat et al. Phys.Lett. B61 (1976) 103



pp- helicity amplitudes A.Sibirtsev Regge parametrization (Gaussian parametrization

pd elastic scattering

Elastic $pd \to pd$ transitions

$$\hat{M}(\mathbf{q},\mathbf{s}) =$$
$$\exp\left(\frac{1}{2}i\mathbf{q}\cdot\mathbf{s}\right)M_{pp}(\mathbf{q}) + \exp\left(-\frac{1}{2}i\mathbf{q}\cdot\mathbf{s}\right)M_{pn}(\mathbf{q}) +$$
$$+\frac{i}{2\pi^{3/2}}\int \exp\left(i\mathbf{q}'\cdot\mathbf{s}\right)\Big[M_{pp}(\mathbf{q}_1)M_{pn}(\mathbf{q}_2) + p\leftrightarrow n\Big]d^2\mathbf{q}'.$$

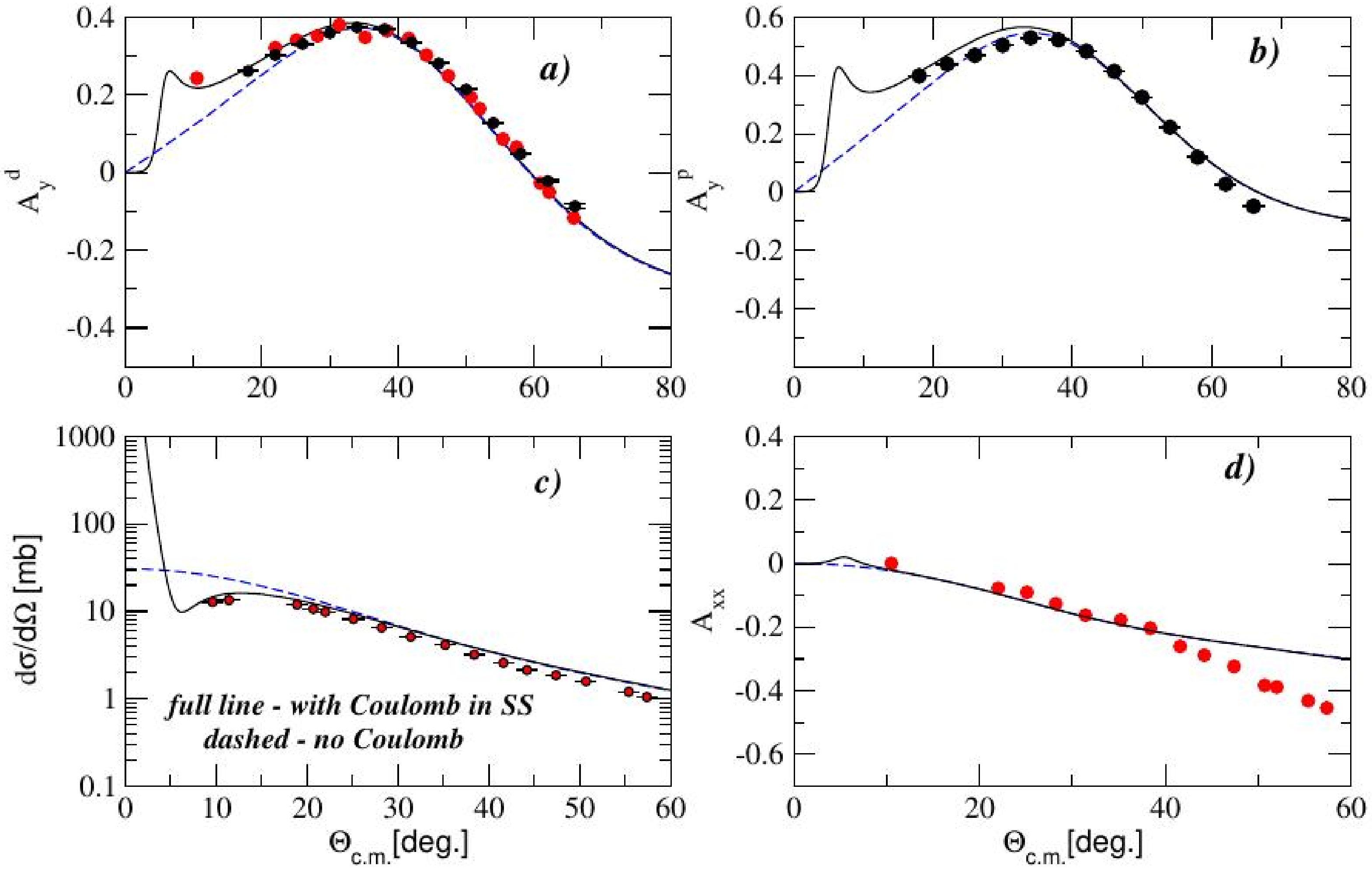
On-shell elastic pN scattering amplitude (**T-even, P-even**)

$$\begin{aligned} M_{pN} &= A_N + (C_N\boldsymbol{\sigma}_1 + C'_N\boldsymbol{\sigma}_2)\cdot\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{k}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{k}}) + \\ &+ (G_N - H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{n}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{n}}) + (G_N + H_N)(\boldsymbol{\sigma}_1\cdot\hat{\mathbf{q}})(\boldsymbol{\sigma}_2\cdot\hat{\mathbf{q}}) \end{aligned}$$

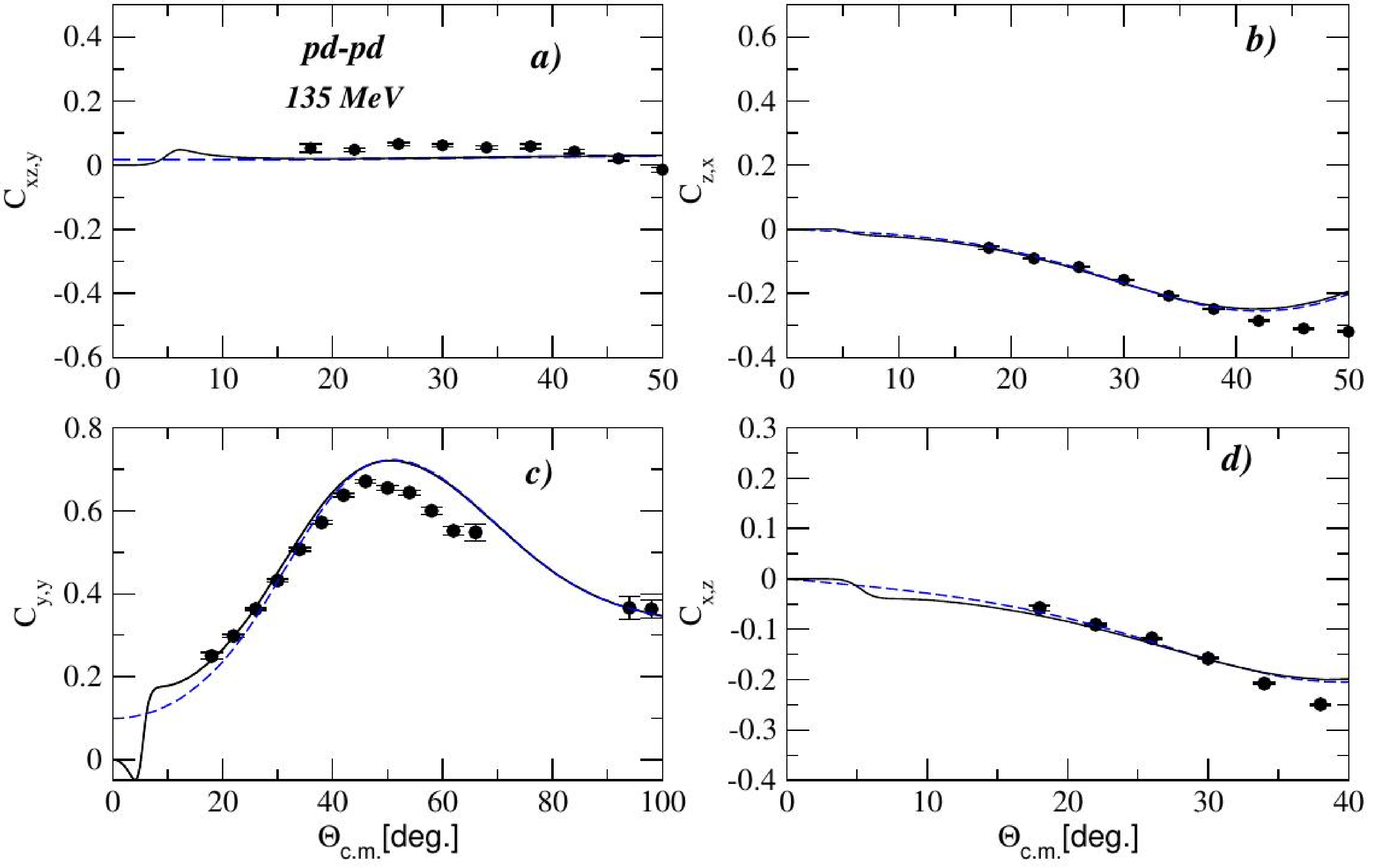
M. Platonova, V. Kukulin, PRC **81** (2010) 014004:

Test calculations: pd elastic scattering at 135 MeV

A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38

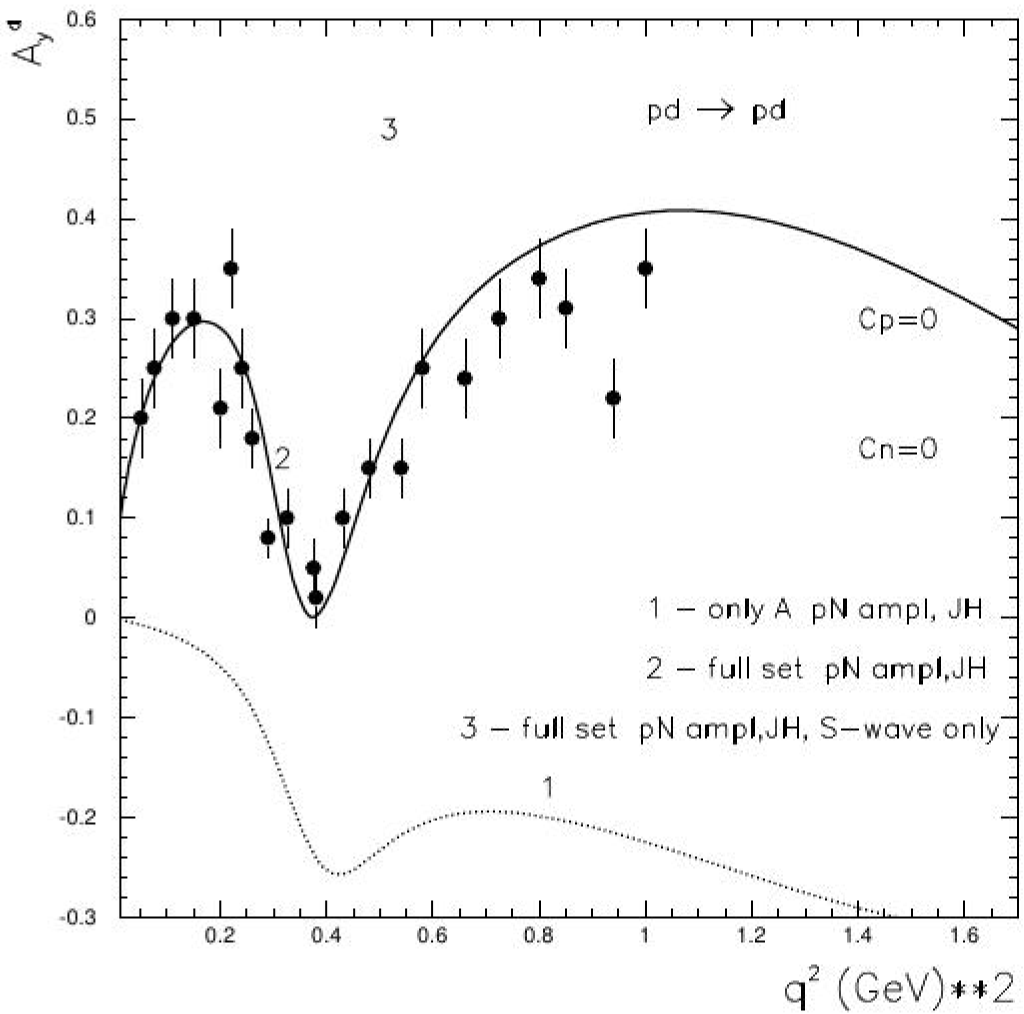


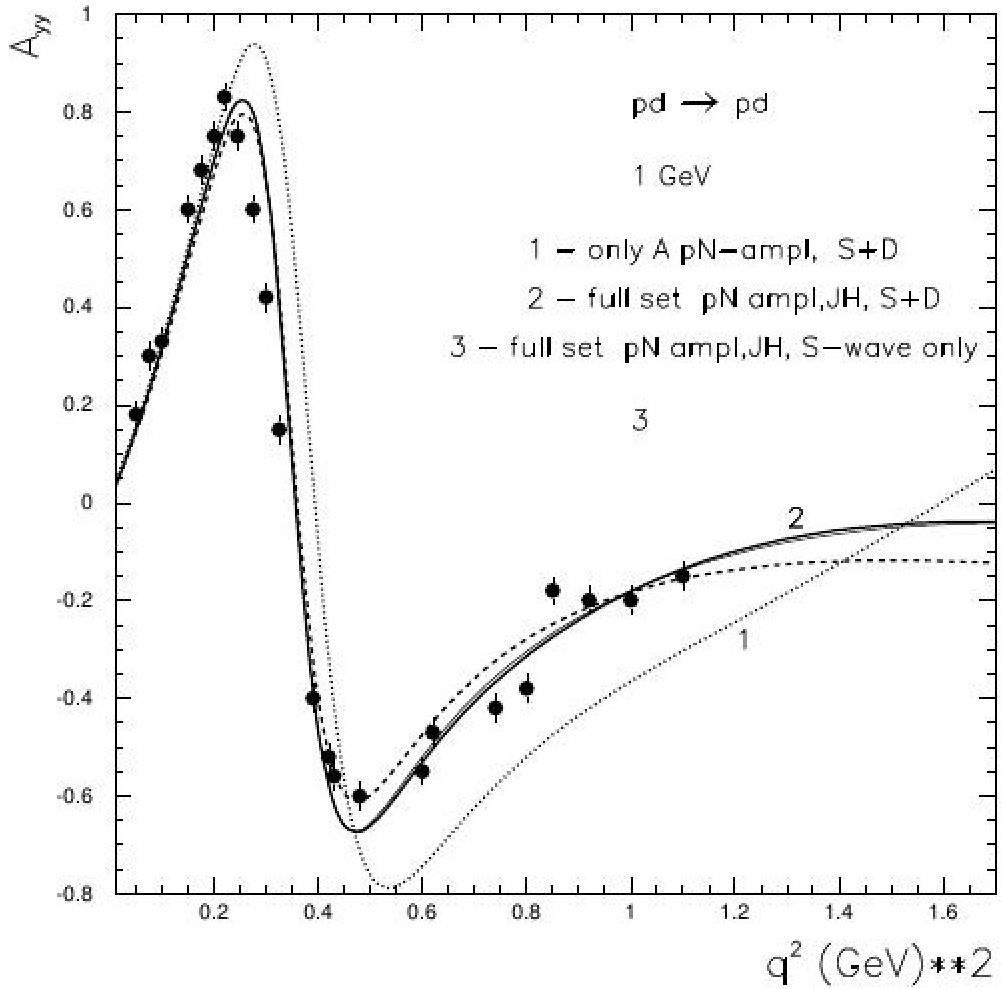
Data: K. Sekiguchi et al. PRC (2002); B. von Przewoski et al. PRC (2006)
See also Faddeev calculations: A.Deltuva, A.C. Fonseca, P.U. Sauer, PRC 71 (2005) 054005.

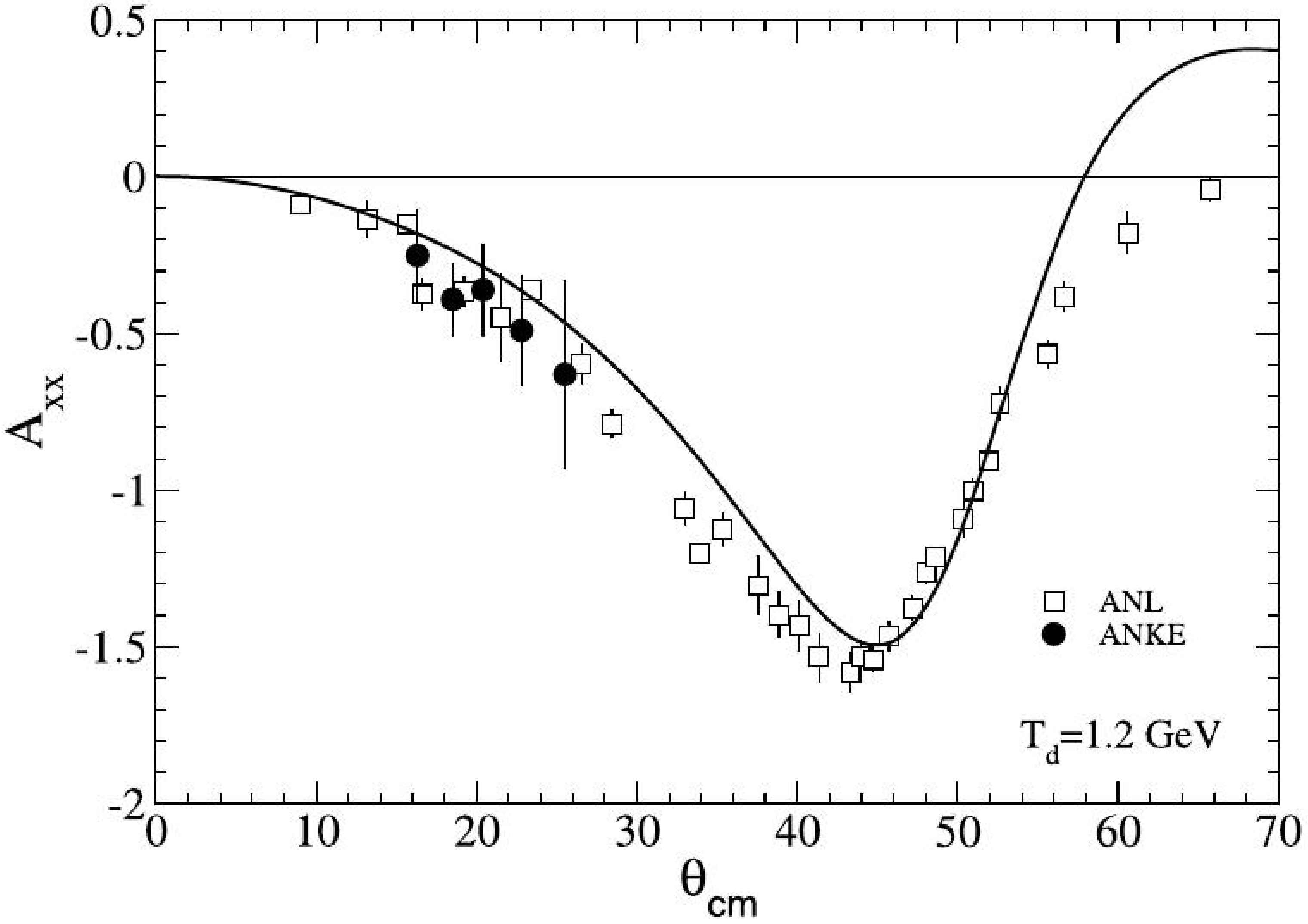


Curves: the modified Glauber model; A.A. Temerbayev, Yu.N.Uzikov, Yad. Fiz. **78** (2015) 38
Data: von B.Przewoski et al. PRC 74 (2006) 064003

Test calculations: pd elastic scattering at 1 GeV







D. Mchedlishvili et al. (ANKE@COSY) Nucl.Phys. A977 (2018)

M.N. Platonova, V.I. Kukulin, EPJ A (2020) 56:132

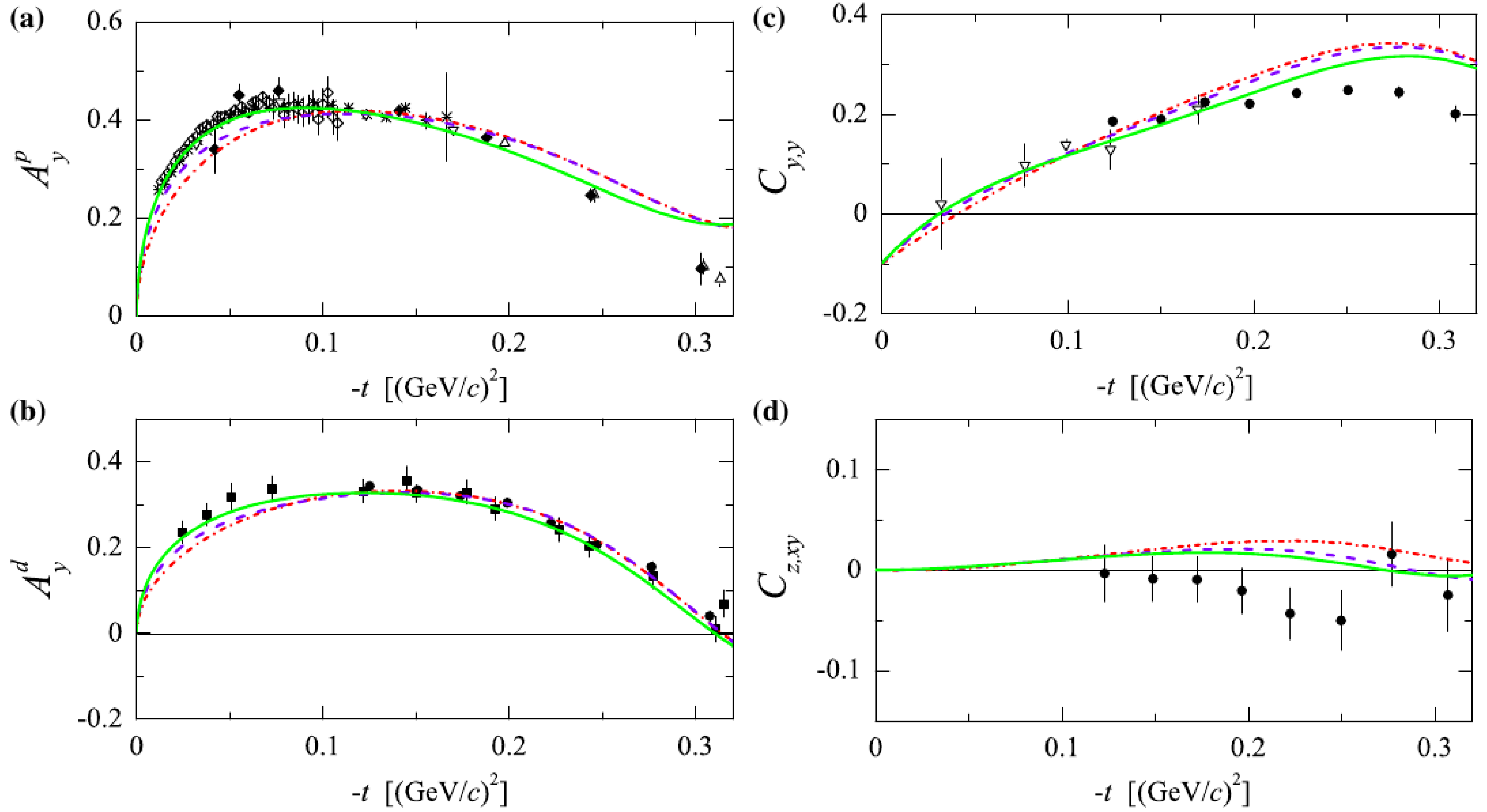
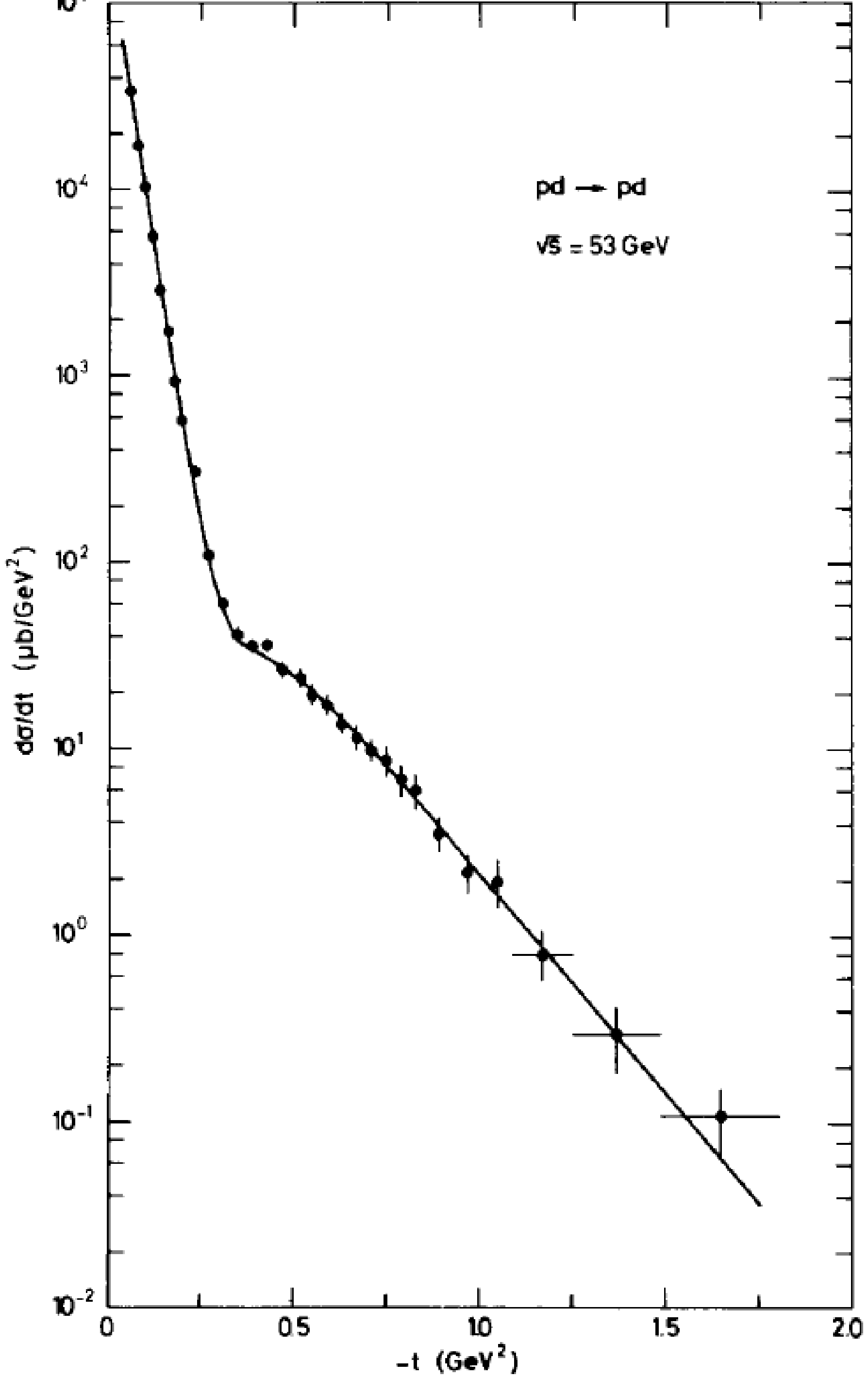
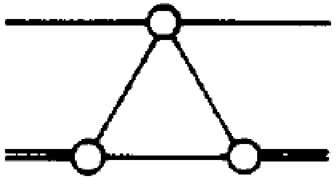


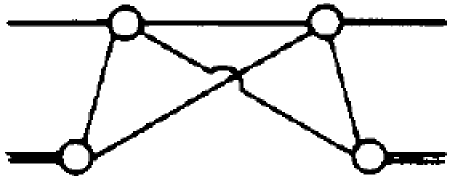
Fig. 8 Proton analyzing power A_y^p (**a**), deuteron analyzing power A_y^d (**b**), vector spin-correlation parameter $C_{y,y}$ (**c**) and tensor spin-correlation parameter $C_{z,xy}$ (**d**) in pd (dp) elastic scattering at the incident (equivalent) proton energy $T_p = 800$ MeV. Dash-dotted (red), dashed (violet) and solid (green) lines show the refined Glauber model calculations with NN amplitudes corresponding to the SAID PWA solution SM16 [35,41], with the modified amplitude C_p and with modified amplitudes C_p and C_n (see Fig. 6), respectively. Experimental data at $T_p = 796$ and 800 MeV are the same as in Figs. 2, 4 and 5



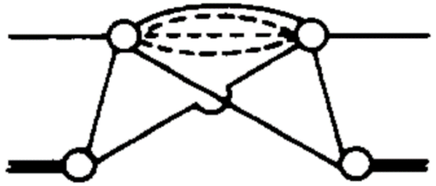
Glauber calculations of the d\sigma/dt for pd-elastic
at ISR energies sqrt{s}=53 and 63 GeV
G.Goggi et al. Nucl. Phys. B149 (1979) 381



a)



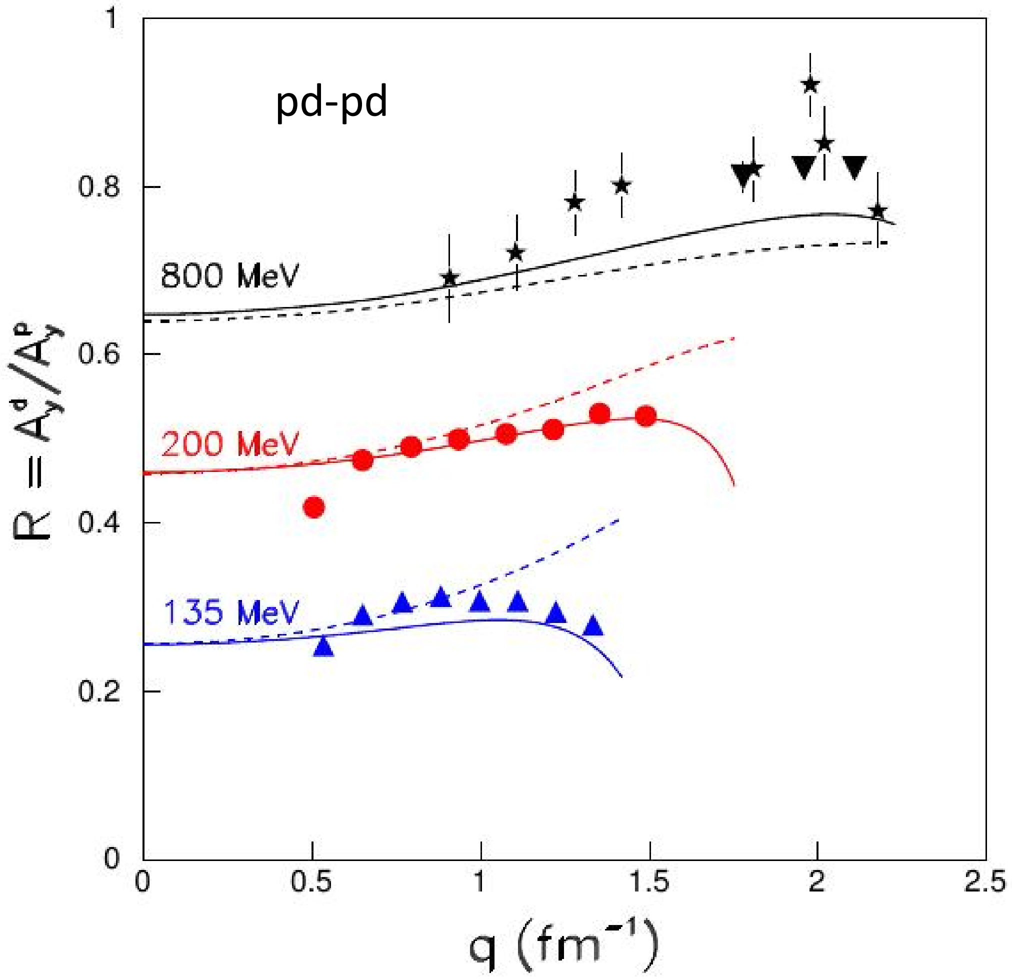
b)



$R = A\_y^d / A\_y^p$

Yu.N.U, C. Wilkin, Phys. Lett. B793 (2019) 224,

R ≠2/3 is sensitive to spin-spin NN terms



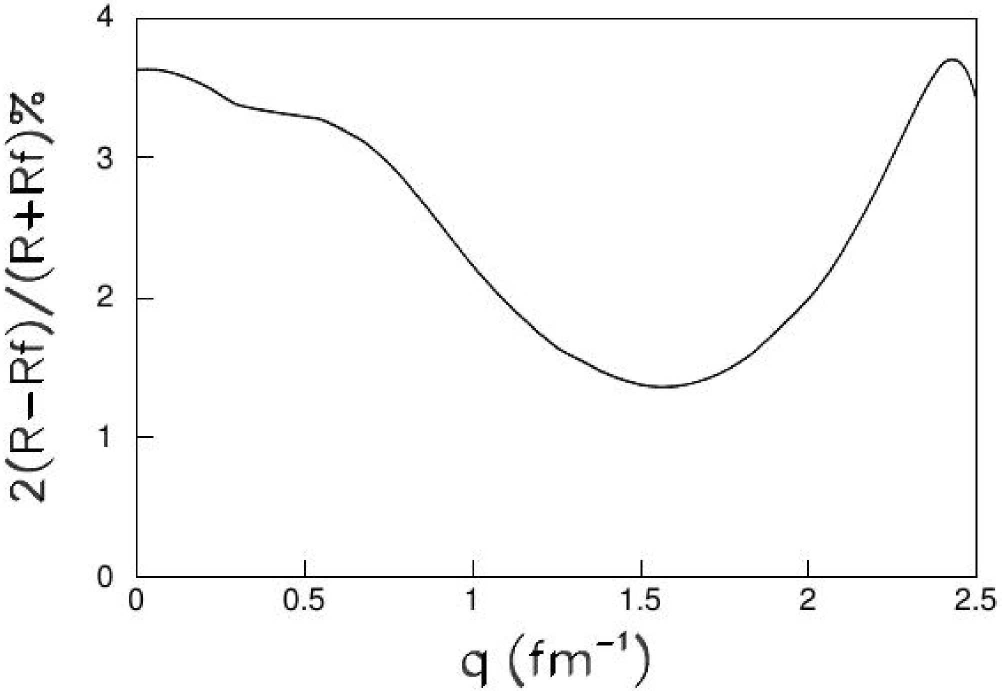
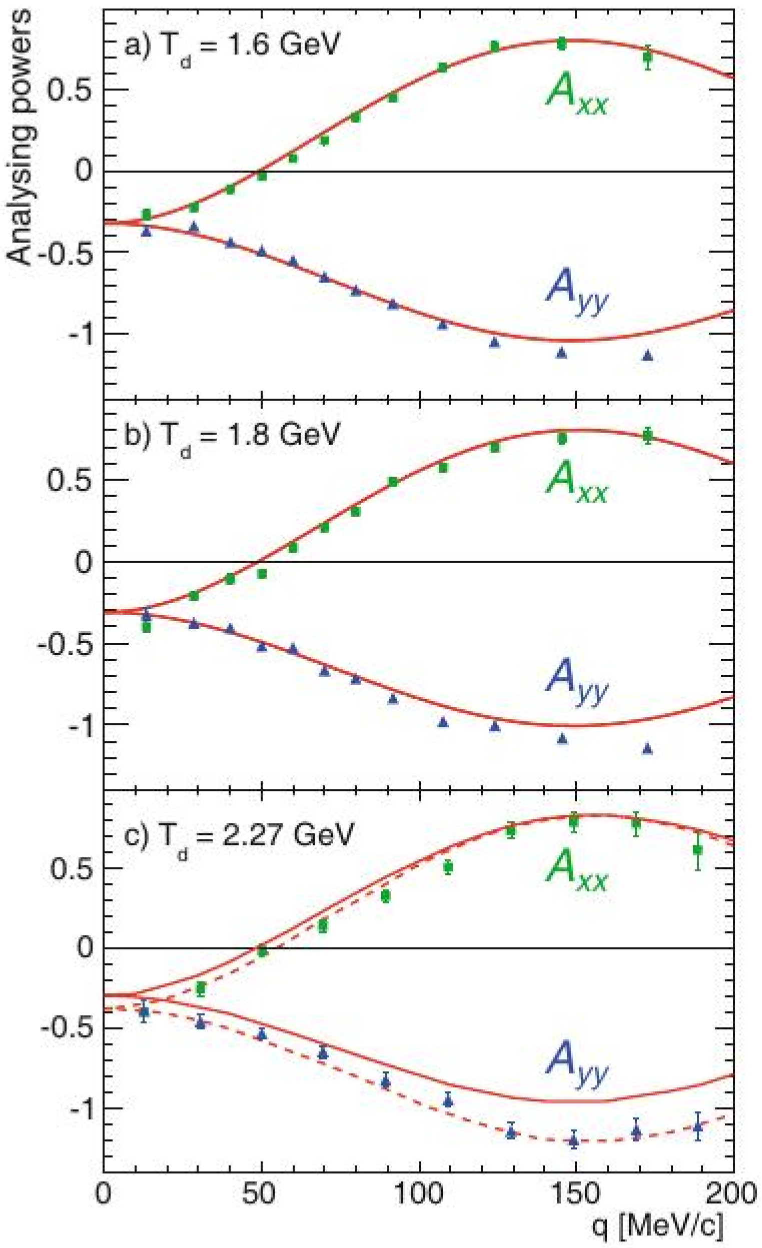
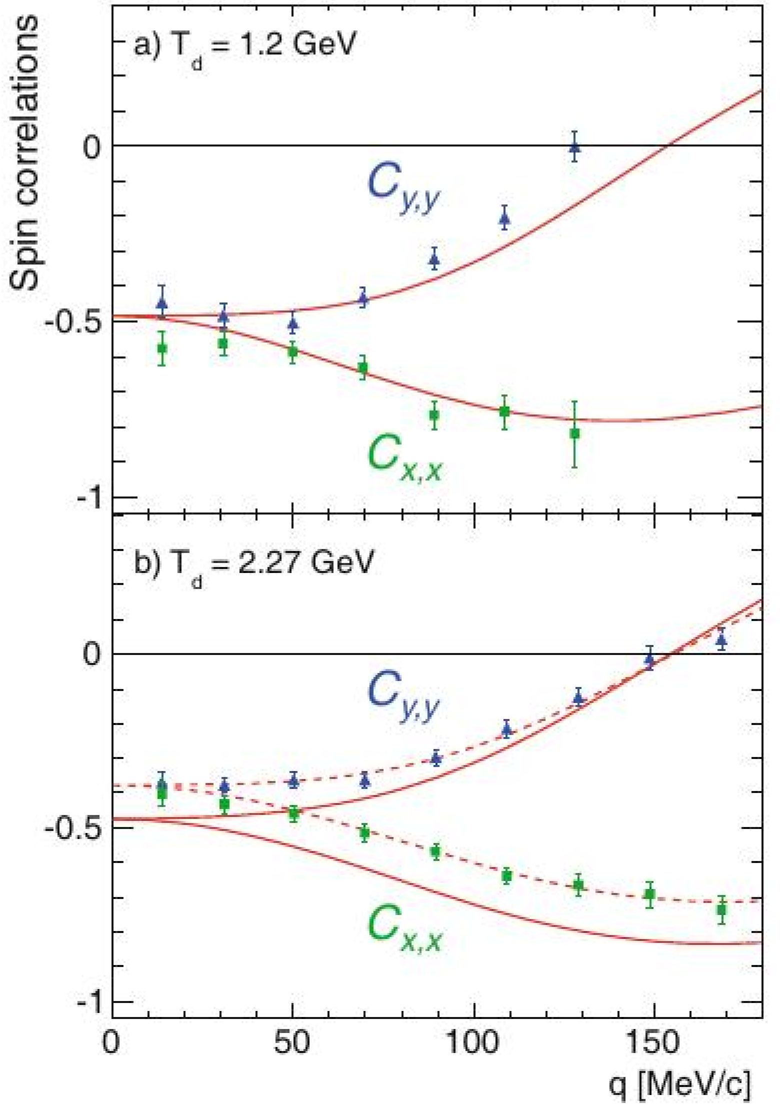


Figure 2: Difference between the predictions of the refined Glauber model [10] without (R) and with (Rf) the NN spin-spin contribution at 800 MeV expressed as a percentage of their average.



'ig. 8. Tensor analysing powers A_{xx} (squares) and A_{yy} (tri- ngles) of the $\vec{d}p \to \{pp\}_s n$ reaction at three beam energies for ›w diproton excitation energy, $E_{pp} < 3\,\text{MeV}$, compared to im-

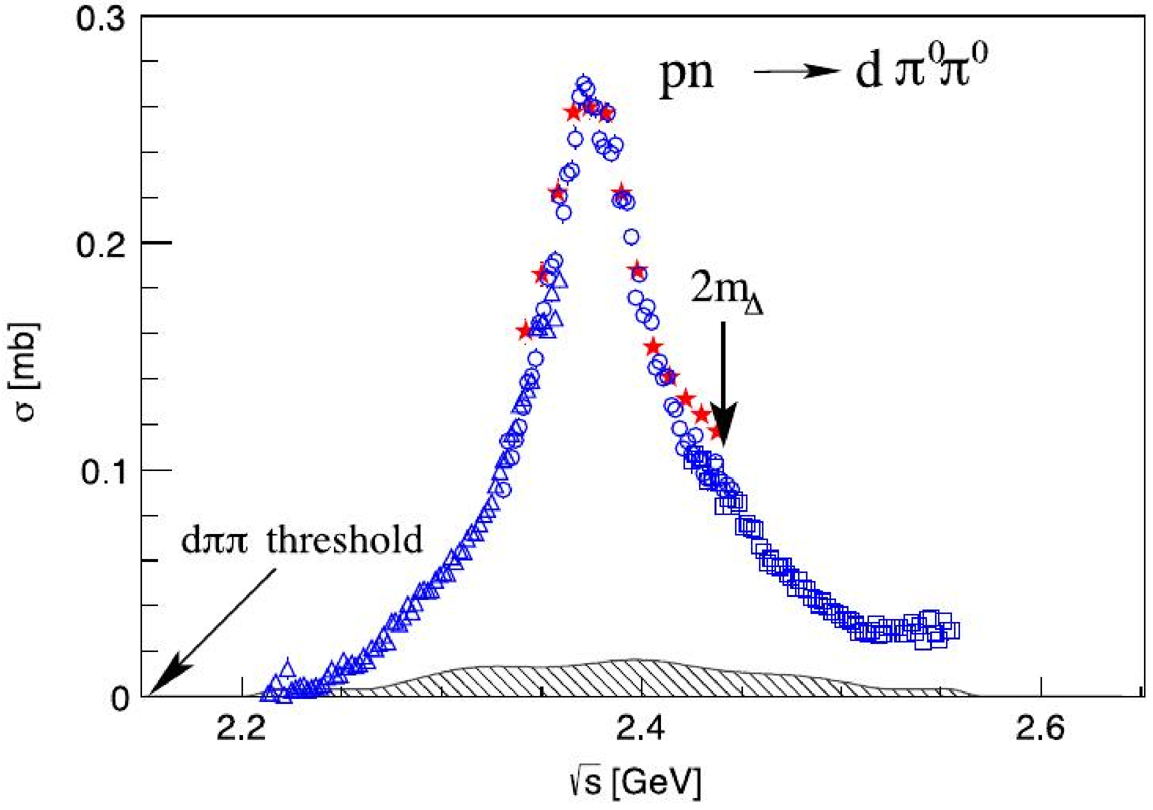


pd-> (pp)+n, E_pp< 3MeV, 1S0 ANKE

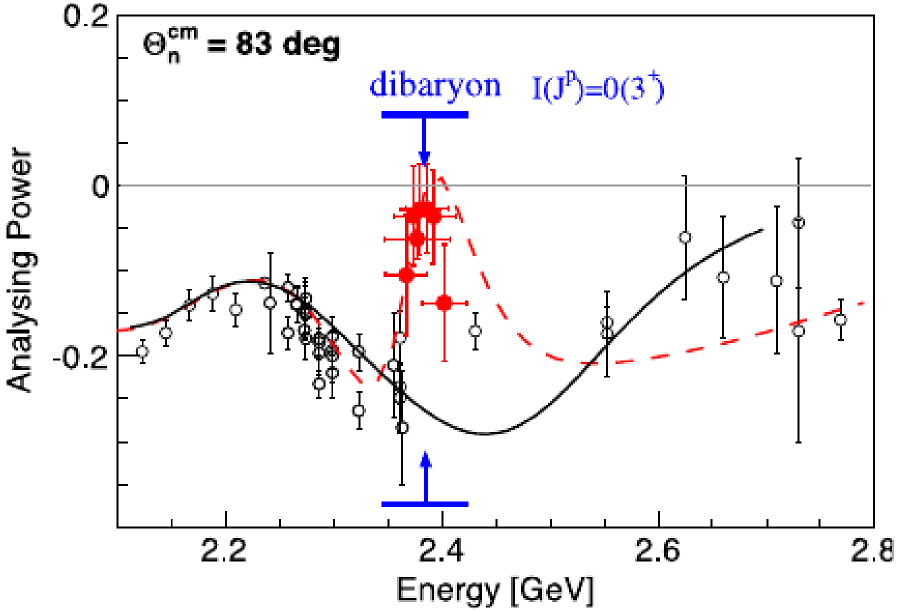
D. Mchedlishvili, et al. EPJA 49 (2013)

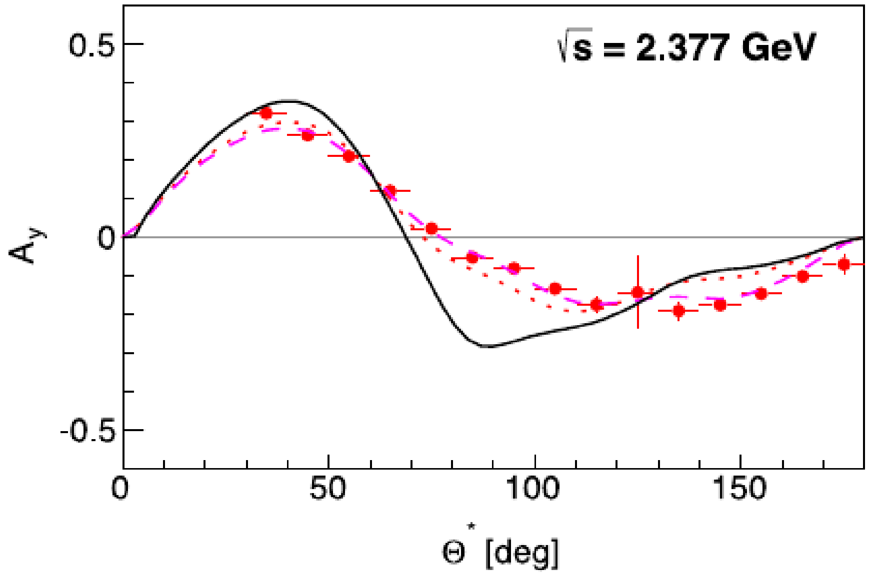
d*(2380) dybarion $J^P = 3^+$

H. Clement / Progress in Particle and Nuclear Physics 93 (2017) 195–242

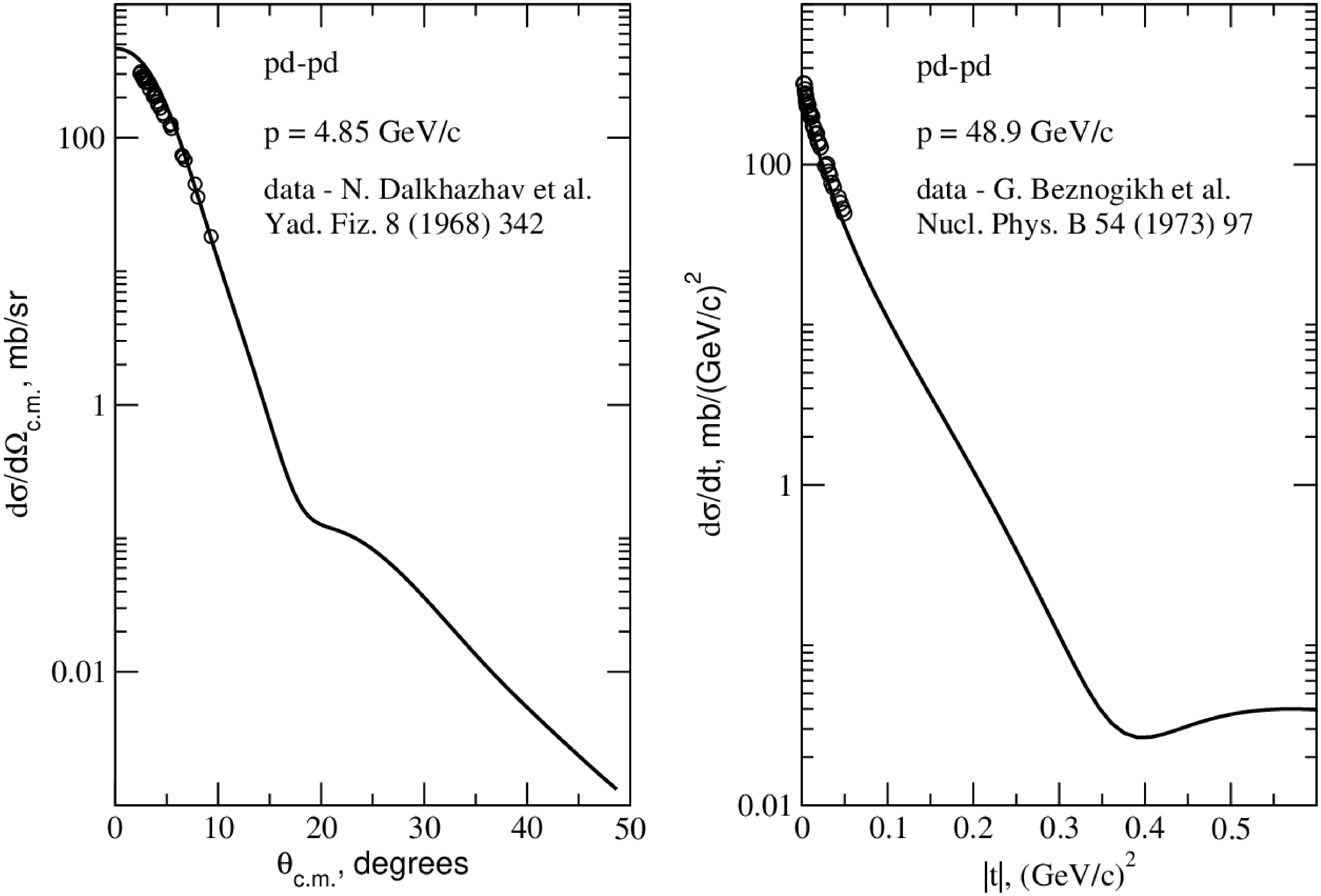


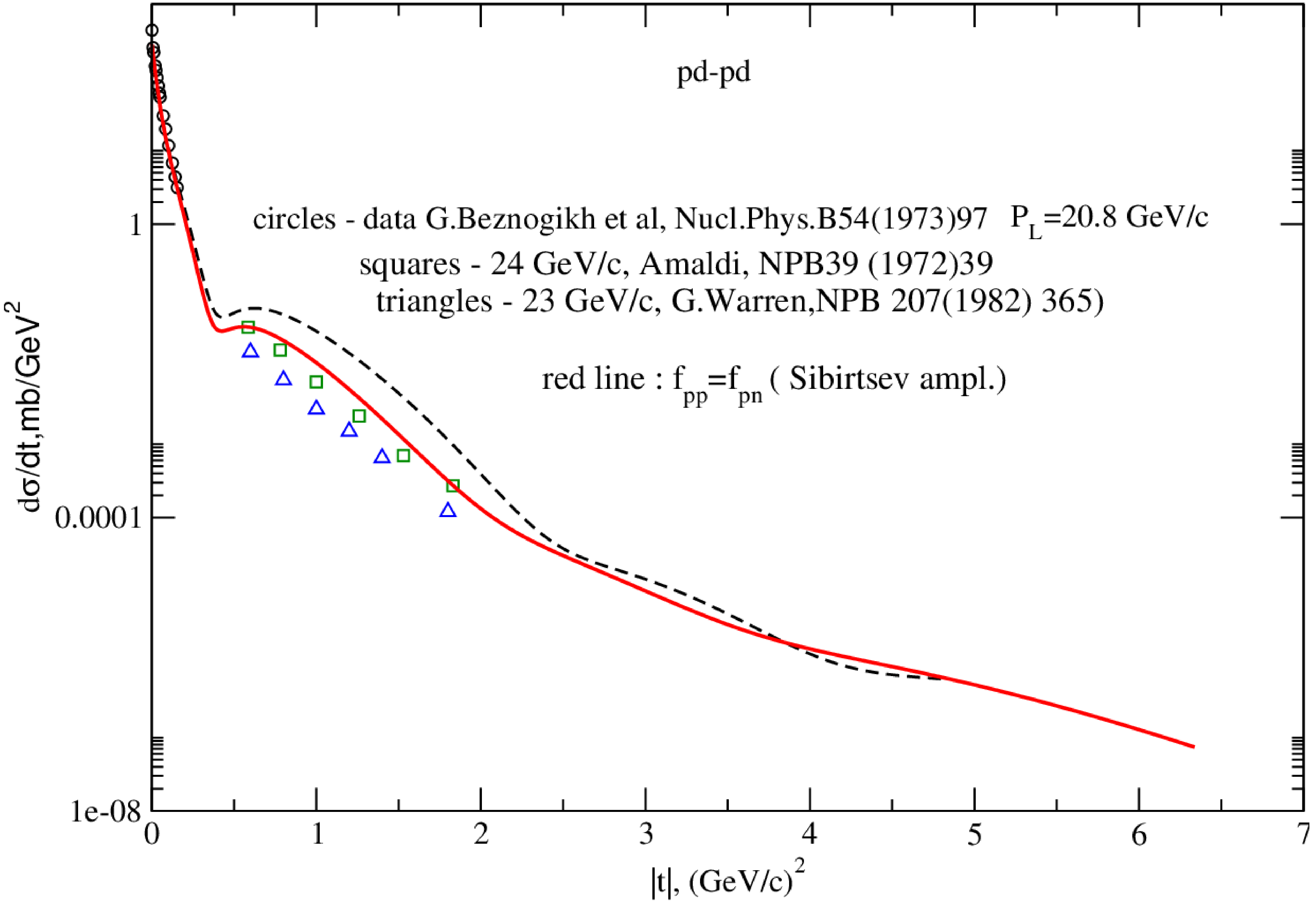
H. Clement / Progress in Particle and Nuclear Physics 93 (2017) 195–242





RESULTS OF pd-pd CALCULATIONS within THE GLAUBER THEORY FOR SPD NICA

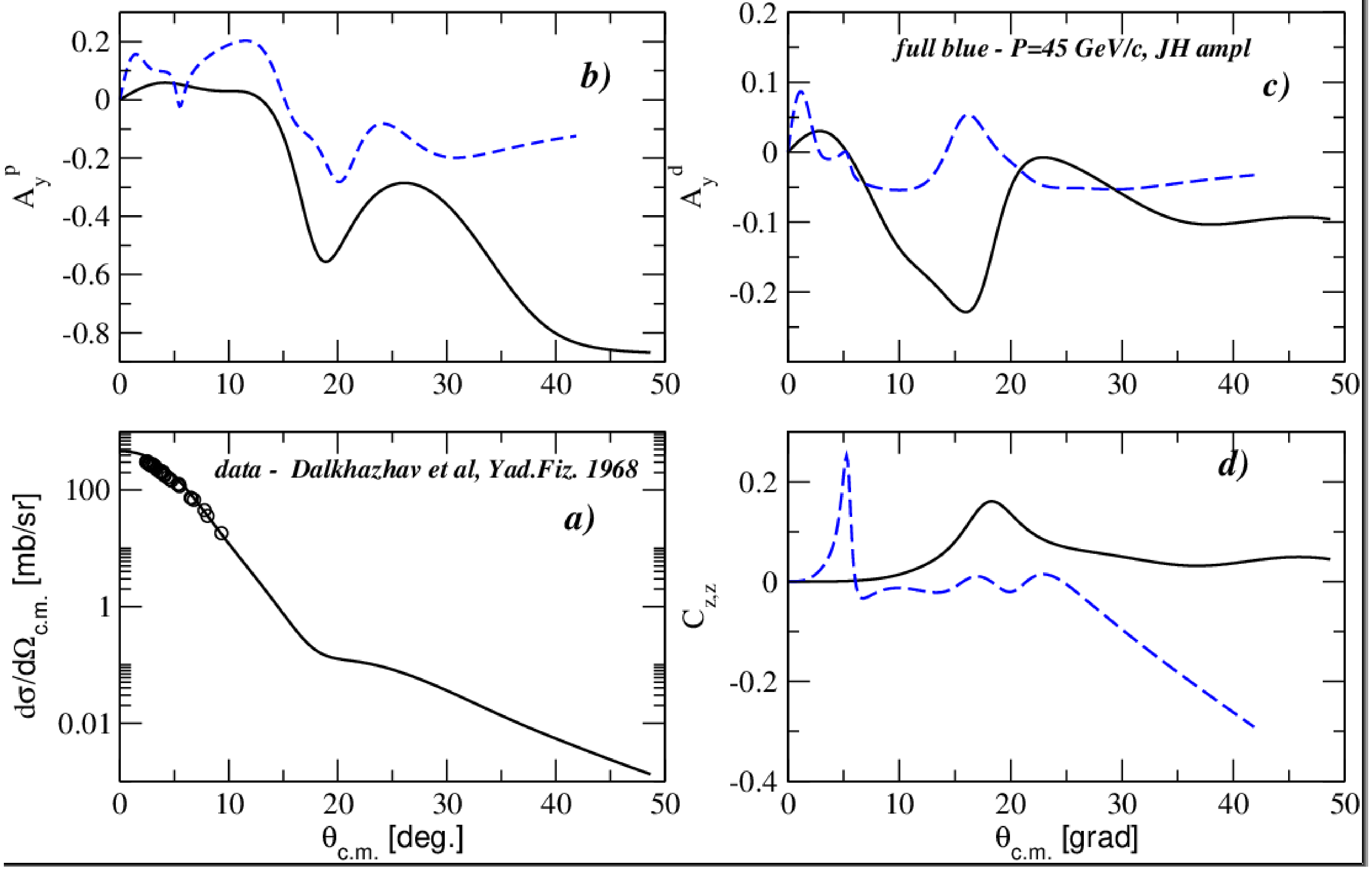

pd-pd
p = 4.85 GeV/c
data - N. Dalkhazhav et al.
Yad. Fiz. 8 (1968) 342
dσ/dΩc.m., mb/sr
θc.m., degrees
100
1
0.01
0
10
20
30
40
50
pd-pd
p = 48.9 GeV/c
data - G. Beznogikh et al.
Nucl. Phys. B 54 (1973) 97
dσ/dt, mb/(GeV/c)2
|t|, (GeV/c)2
100
1
0.01
0
0.1
0.2
0.3
0.4
0.5



pd-pd
circles - data G.Beznogikh et al, Nucl.Phys.B54(1973)97 P_L=20.8 GeV/c
squares - 24 GeV/c, Amaldi, NPB39 (1972)39
triangles - 23 GeV/c, G.Warren,NPB 207(1982) 365)
red line : $f_{pp}=f_{pn}$ (Sibirtsev ampl.)
dσ/dt,mb/GeV^2
|t|, (GeV/c)^2
1
0.0001
1e-08
0
1
2
3
4
5
6
7

pd- elastic

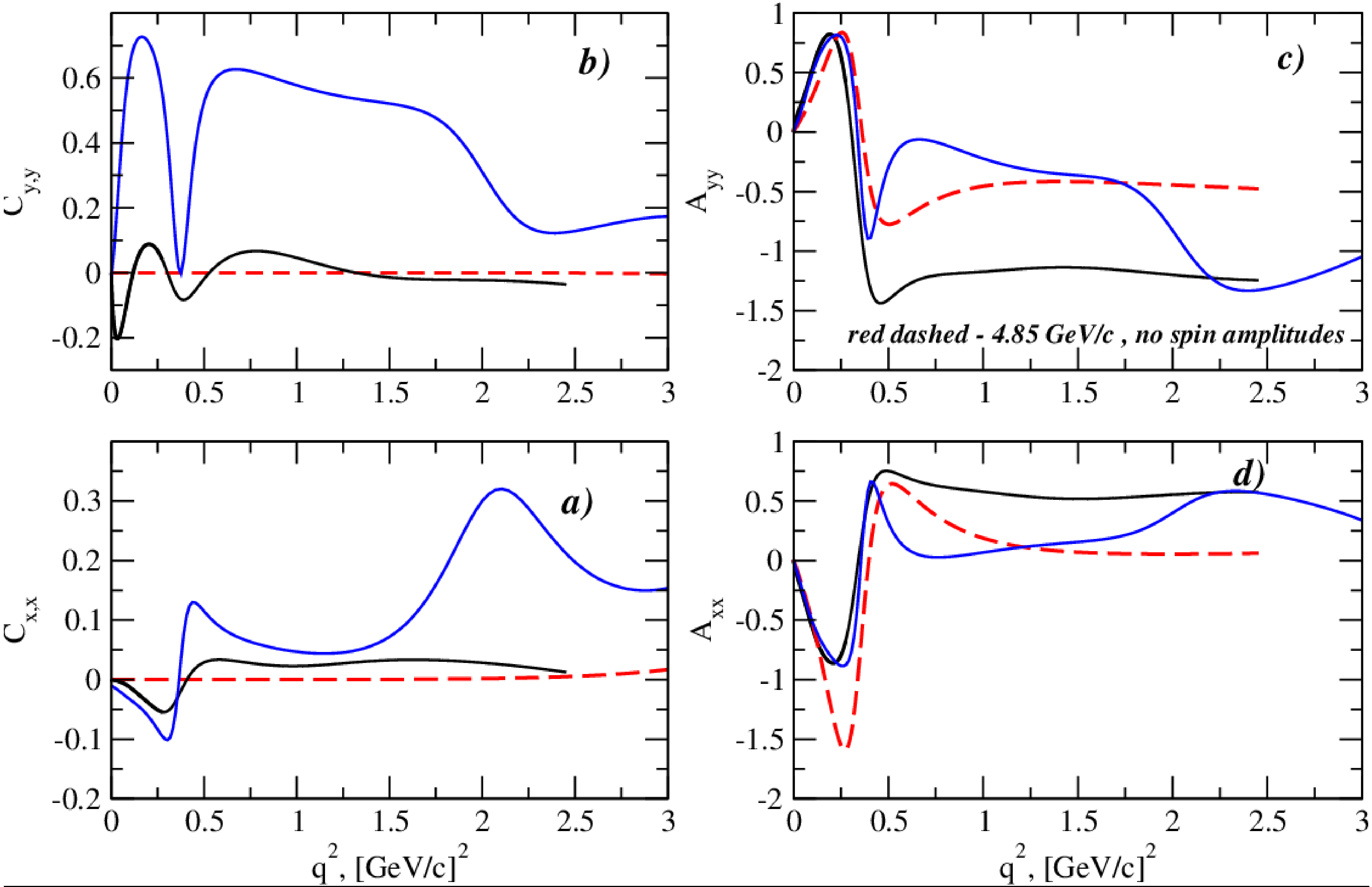
full black - P_L=4.85 GeV/c with JH; dashed blue - 45 GeV/c with JH-3 ampl.



pd- elastic

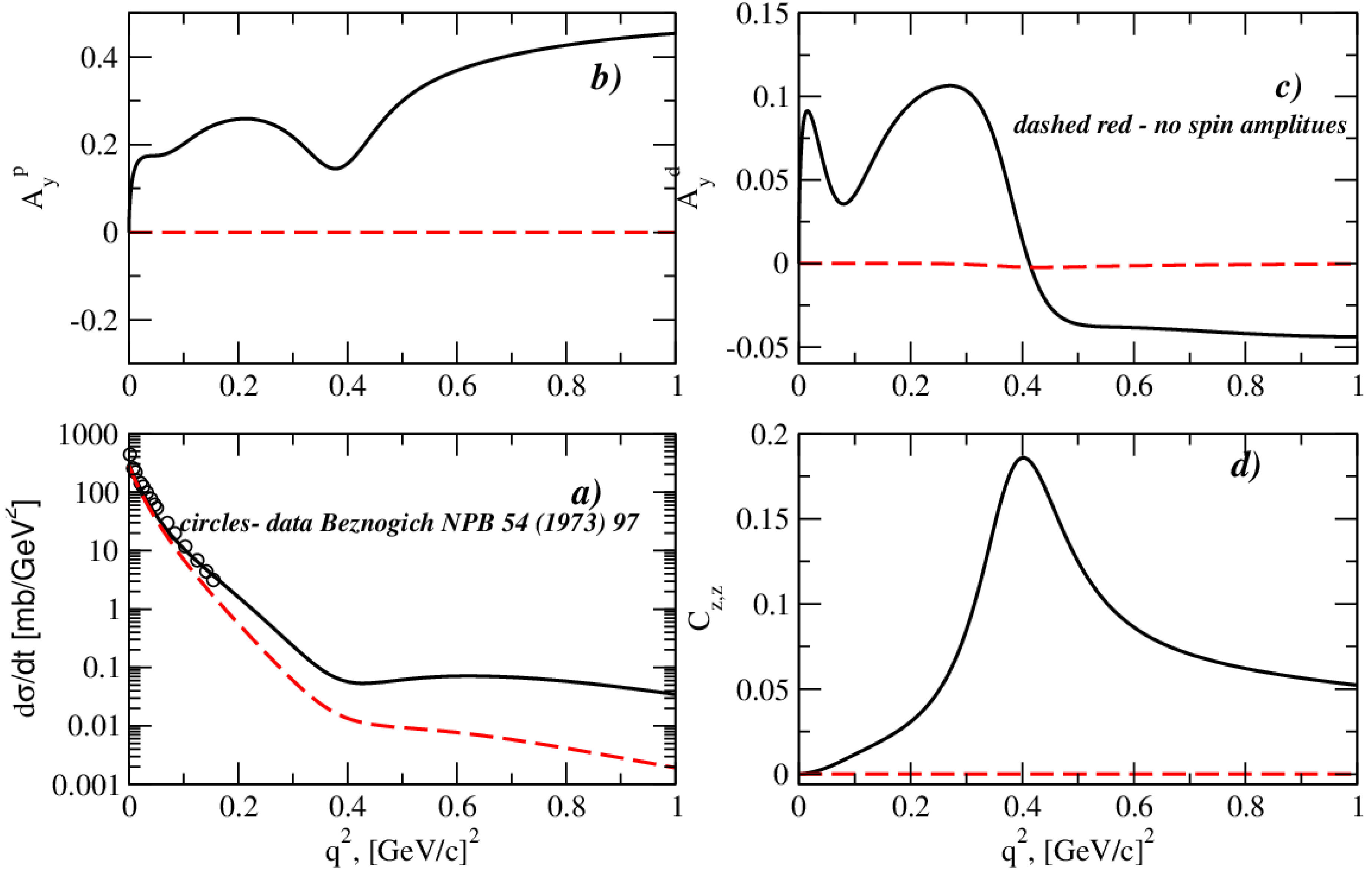
full black - P_L=4.85 GeV/c with Sibirtsev amplitudes; full blue - 45 GeV/c (JH)

dashed red - 4.85 GeV/c without spin dependent pN amplitudes



pd- elastic

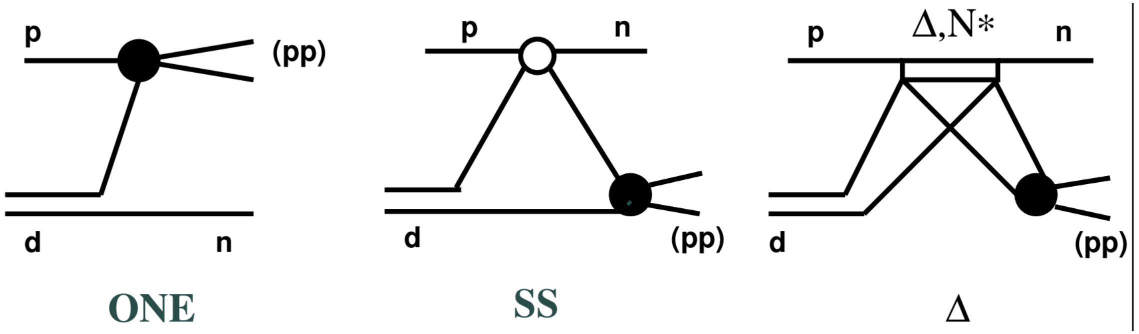
full black - P_L=20.4 GeV/c with Sibirtsev amplitudes

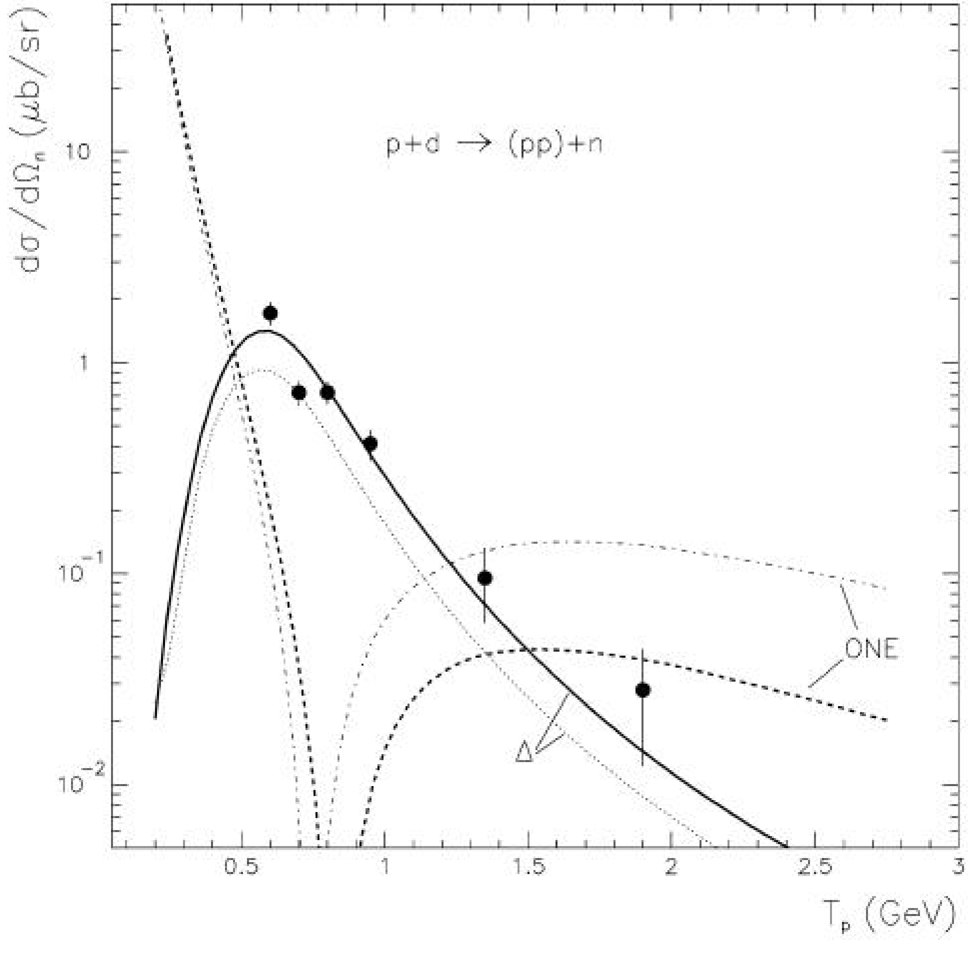


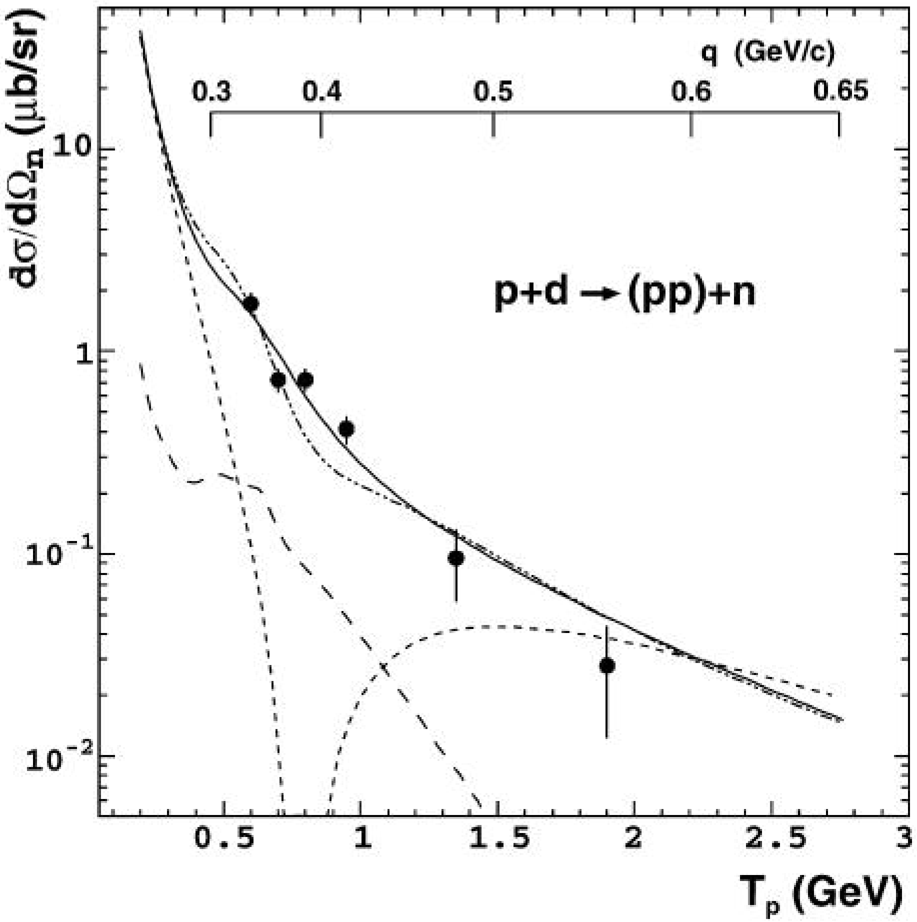
Quasielastic scattering

$$p + d \rightarrow \{pp\}(^1S_0) + n$$

J. Haidenbauer, Yu. Uzikov, PLB (2003)







$$p + d \to \{pp\}_s + n$$

$$\mathcal{F} = \mathcal{A}(\mathbf{e}\cdot\mathbf{k})(\boldsymbol{\sigma}\cdot\mathbf{k}) + \mathcal{B}\mathbf{e}\cdot\boldsymbol{\sigma},$$

$$p + n \to n + p$$

$$f_{12}^{collin} = \alpha + \beta(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) + (\varepsilon - \beta)(\boldsymbol{\sigma}_1\cdot\mathbf{k})(\boldsymbol{\sigma}_2\cdot\mathbf{k}).$$

$$\mathcal{A} = (\epsilon - \beta)S(Q/2), \quad \mathcal{B} = \beta S(Q/2)$$

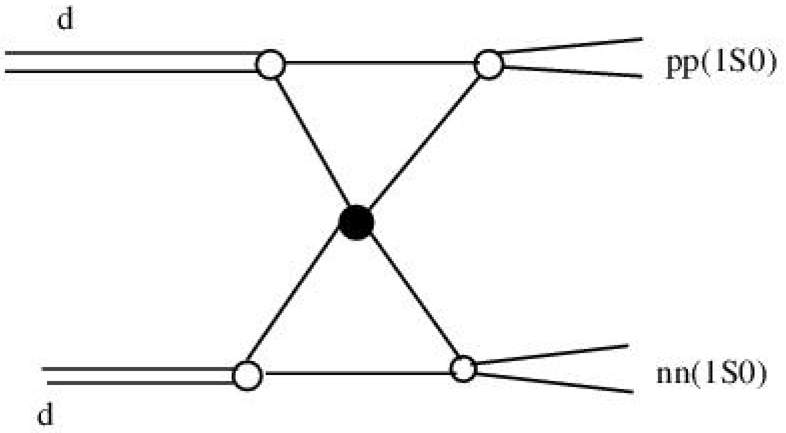
$$d\sigma_0 = \frac{1}{3}\mathcal{K}\left\{|\varepsilon|^2 + 2|\beta|^2\right\},$$

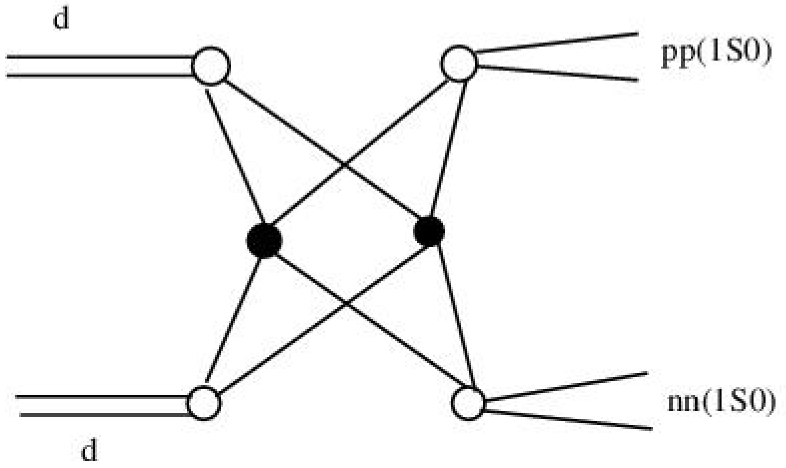
$$T_{20} = \frac{1}{\sqrt{2}}A_{zz} = \sqrt{2}\frac{|\beta|^2 - |\varepsilon|^2}{|\varepsilon|^2 + 2|\beta|^2},$$

$$C_{x,x} = C_{y,y} = -2\frac{Re\varepsilon\beta^*}{|\varepsilon|^2 + 2|\beta|^2},\ C_{xz,y} = -C_{yz,x} = 3\frac{Im\beta\varepsilon^*}{|\varepsilon|^2 + 2|\beta|^2}.$$

Complete polarization experiment gives: $|\varepsilon|, |\beta|, \mathrm{Re}\,\varepsilon\beta^*, \mathrm{Im}\,\varepsilon\beta^*$

dd- elastic and quasi-elastic scattering





Search for T-invariance violation in double polarized pd - scattering

(**see also talk by N. Nikolaev today**)

T-even P-even

$$M_N(\mathbf{p},\mathbf{q};\boldsymbol{\sigma},\boldsymbol{\sigma}_N)$$
$$= A_N + C_N\boldsymbol{\sigma}\hat{\mathbf{n}} + C'_N\boldsymbol{\sigma}_N\hat{\mathbf{n}} + B_N(\boldsymbol{\sigma}\hat{\mathbf{k}})(\boldsymbol{\sigma}_N\hat{\mathbf{k}})$$
$$+ (G_N + H_N)(\boldsymbol{\sigma}\hat{\mathbf{q}})(\boldsymbol{\sigma}_N\hat{\mathbf{q}}) + (G_N - H_N)(\boldsymbol{\sigma}\hat{\mathbf{n}})(\boldsymbol{\sigma}_N\hat{\mathbf{n}})$$

T-odd P-even , M.Simonius,PRL 1997

$$t_{pN} = h_N[(\boldsymbol{\sigma}\cdot\mathbf{k})(\boldsymbol{\sigma}_N\cdot\mathbf{q}) + (\boldsymbol{\sigma}_N\cdot\mathbf{k})(\boldsymbol{\sigma}\cdot\mathbf{q})$$
$$- \tfrac{2}{3}(\boldsymbol{\sigma}_N\cdot\boldsymbol{\sigma})(\mathbf{k}\cdot\mathbf{q})]/m_p^2$$
$$+ g_N[\boldsymbol{\sigma}\times\boldsymbol{\sigma}_N]\cdot[\mathbf{q}\times\mathbf{k}][\boldsymbol{\tau}-\boldsymbol{\tau}_N]_z/m_p^2$$
$$+ g'_N(\boldsymbol{\sigma}-\boldsymbol{\sigma}_N)\cdot i\,[\mathbf{q}\times\mathbf{k}][\boldsymbol{\tau}\times\boldsymbol{\tau}_N]_z/m_p^2.$$

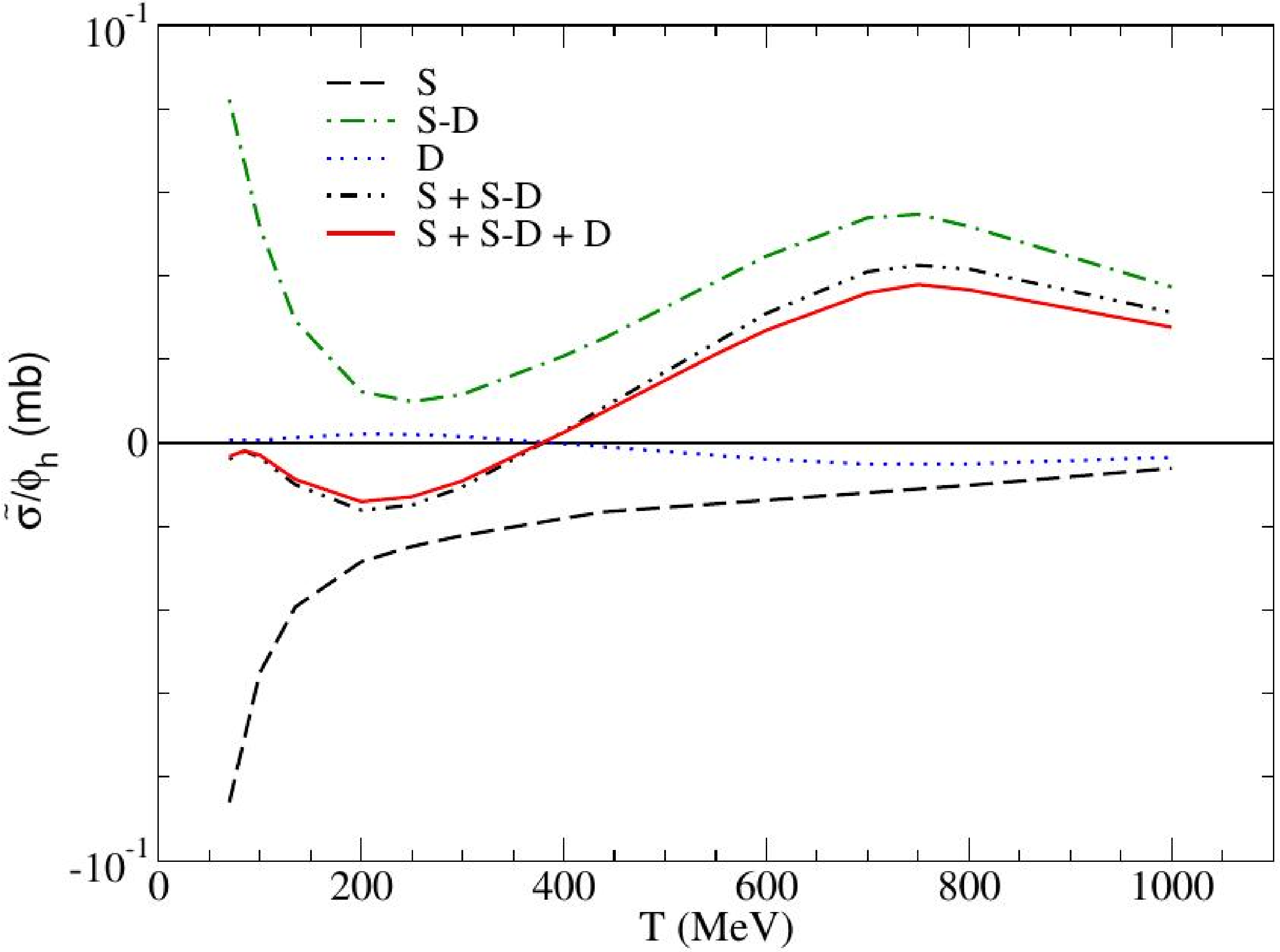
Null-test signal:

$$\tilde{g} = \frac{i}{4\pi m_p}\int_0^\infty dq\,q^2\Big[S_0^{(0)}(q) - \sqrt{8}S_2^{(1)}(q) - 4S_0^{(2)}(q)$$
$$+\sqrt{2}\frac{4}{3}S_2^{(2)}(q) + 9S_1^{(2)}(q)\Big][-C'_n(q)\,h_p + C'_p(q)(g_n - h_n)]$$

$$C' \approx i\phi_5 + iq/2m(\phi_1 + \phi_3)/2$$

Yu.N.U., A.A. Temerbayev, PRC 92 (2015) 014002;
Yu.N.U., J. Haidenabuer, PRC 94 (2016) 035501.

$$\sigma_{tot} = \underbrace{\sigma_0 + \sigma_1 \mathbf{p}^p \cdot \mathbf{P}^d + \sigma_2(\mathbf{p}^p \cdot \hat{\mathbf{k}})(\mathbf{P}^d \cdot \hat{\mathbf{k}}) + \sigma_3 P_{zz}}_{T-even, P-even} + \underbrace{\widetilde{\sigma}_{tvpc} p_y^p P_{xz}^d}_{T-odd, P-even}$$



Yu.N. Uzikov, J.Haidenbauer, PRC 94 (2016) 035501

Conclusion and outlook

- Measurement of spin observables ($d\sigma/dt$, $A_y^p, A_y^d, A_{yy}, A_{xx}, C_{i,j}$) of pd- elastic, $pd \to n\{pp\}_s$, $dd \to dd$, $dd \to \{pp\}_s + \{nn\}_s$ at SPD NICA is important. Available Regge parameterizations for pp amplitudes at $P_L = 3 - 50$ GeV/c (A. Sibirtsev et al. 2010; Van Orden; others) can be used for calculation of these observables within the Glauber theory. Comparison between data and theory **will provide a clean test for the pp- and pn- elastic amplitudes**.

- The ratio $R = A_y^d / A_y^p$ at small q being measured with a high accuracy ($\sim 1\%$) gives an information about **spin-spin transversal NN amplitudes**.

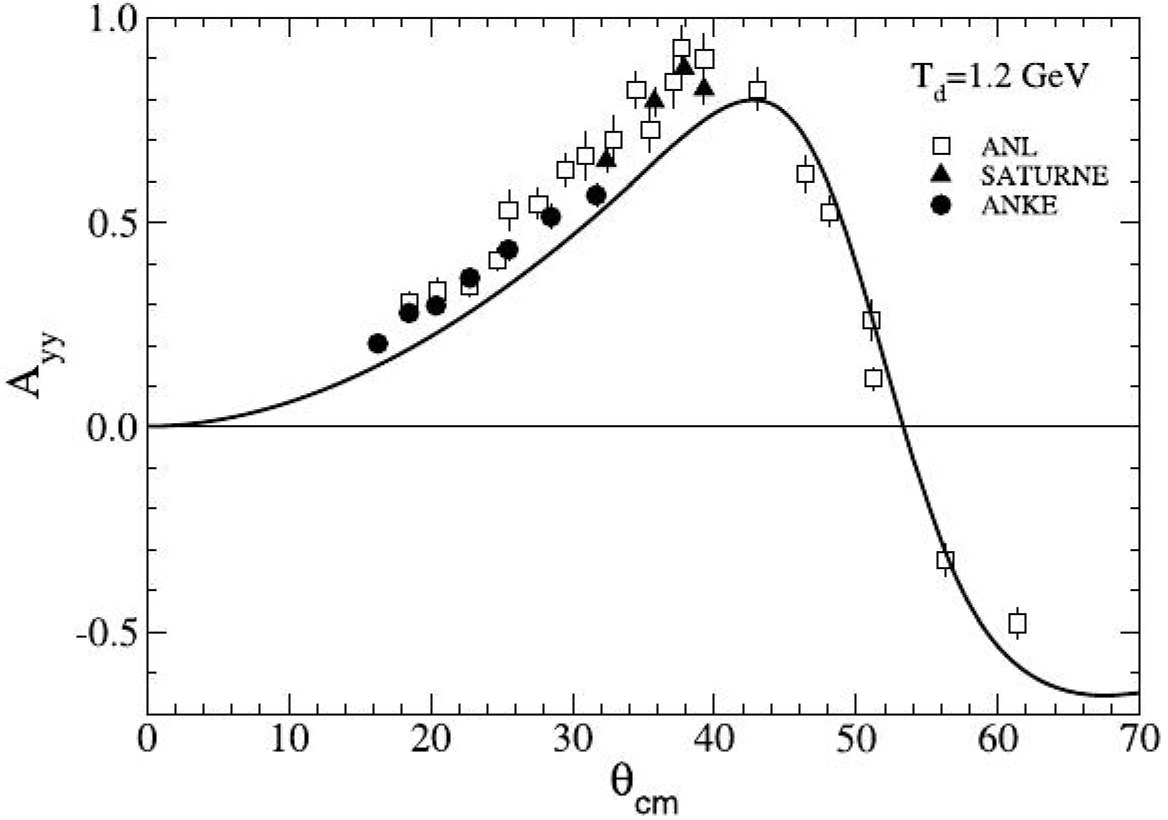
- The Regge pp-formalism provides an **access to $\bar{p}N$ elastic**, but actually was not tested in double spin onservables. The necessary data A_{NN} can be obtained at SPD NICA $\Longrightarrow$ to test the pp-amplitudes, to study **"oscillation effects"** and to test the **dispersion relations** for pN-data.

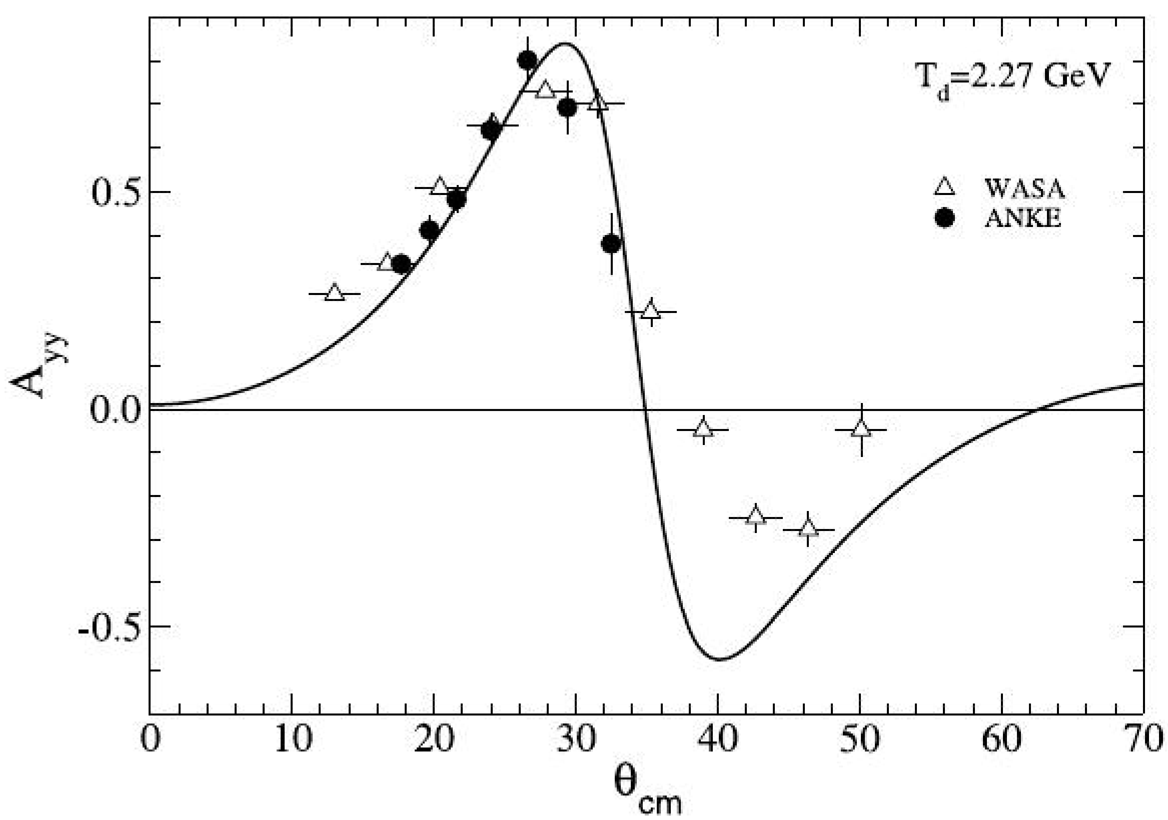
- **Search of T-invariance violation** in double polarized pd and dd scattering at energies corresponding to **the early Universe seems to be very important**. The elastic (T-even) pN- amplitudes at SPD NICA energies are necessary to analyse data of the dedicated experiment.

Thank you for attention!

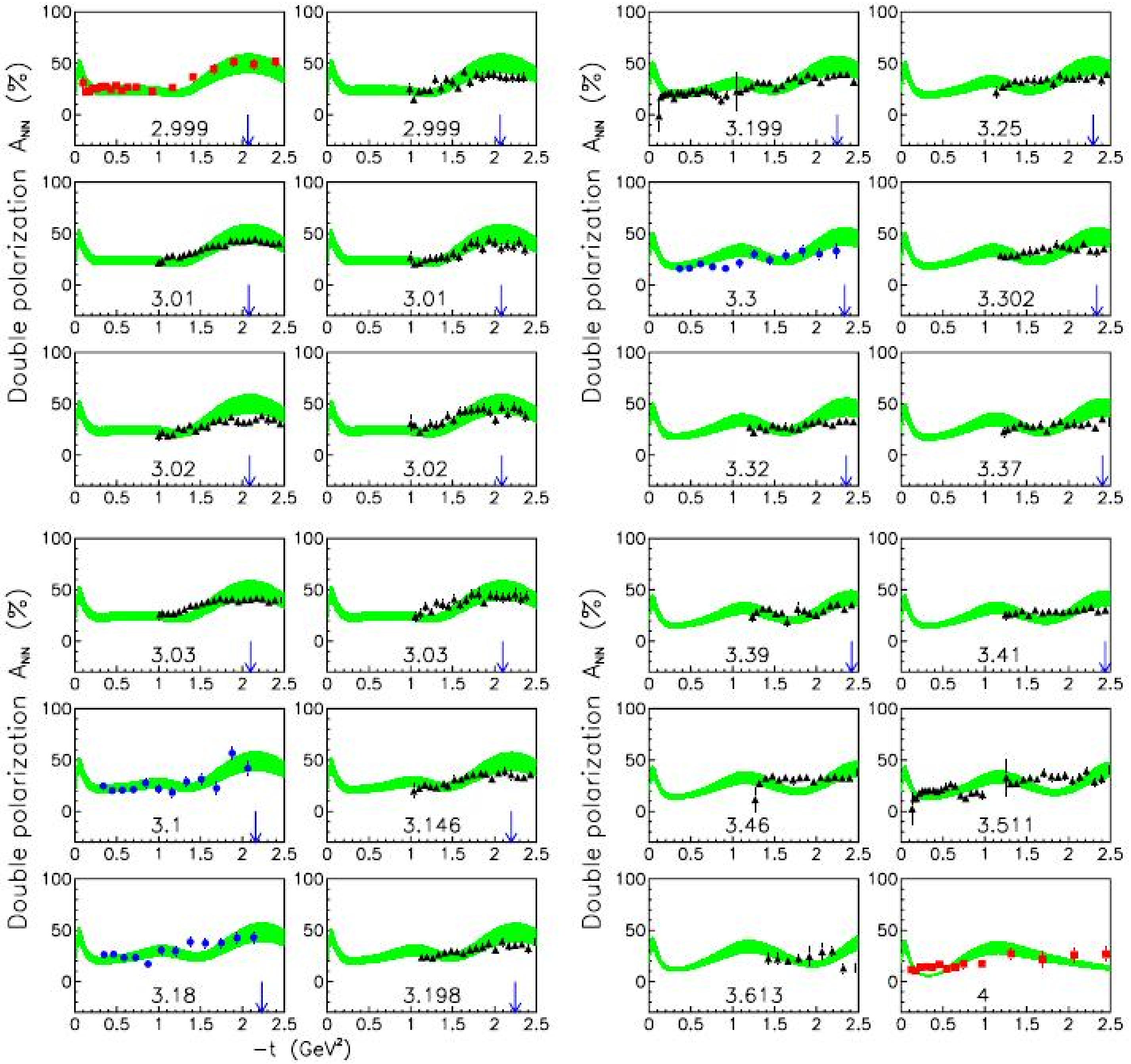
APPENDIX

D. Mchedlishvili et al. Nucl.Phys. A 977 (2018) 14 , pd-elastic





A. Sibirtsev et al, (2010);
Only 3-4 GeV/c



– *Why search for Time-invariance Violating P-conserving Effects?*

- The T- violating, P-violating (TVPV) effects arise in SM through CP violating phase of CKM matrix and through the QCD $\theta-$ term. EDM.

- T-violating P-conserving (TVPC) (flavor-conserving) effects do not arise in SM as Fundamental interactions,

  although can be generated through weak corrections to TVPV interactions

  ⋆ Observed (in K^0, B^0) CP violation in SM leads to simultaneous violation of T- and P-invariance.
  Therefore, to produce T-odd P-even term one should have one additional P-odd term in the effective interaction: $\mathbf{g} \sim \mathbf{M^4 G_F^2} \sin\delta \sim \mathbf{10^{-10}}$

  V.P. Gudkov, Phys. Rep. **212**(1992)77

  ⋆ …much larger g is not excluded by unknown interaction beyond the SM.

  ⋆ **Experimental limits on TVPC effects are much weaker than for EDM.**

– *Planned experiments to search for CP violation beyond the SM*

• Detecting a non-zero **EDM** of elementary fermion (neutron, atoms, charged particles). The current experimental limit

$$|d_n| \leq 2.9 \times 10^{-26} e\, cm$$

is much less as compared the SM estimation (B.H.J. McKellar et al. PLB 197 (1987)
$1.4 \times 10^{-33} e\, cm \leq |d_n| \leq 1.6 \times 10^{-31} e\, cm$

• Search for CP violation in the **neutrino sector** ($\theta_{13} \neq 0$, then generation of lepton asymmetry and via $B - L$ conservation to get the BAU).

Thouse are T-violating and Parity violating (TVPV) effects.

Much less attention was paid to T-violating P-conserving (TVPC) flavor conserving effects.

Search for T-violation in other processes

- Search for T-violation in decays

A.G. Beda, V.P. Skoy, Elem.Chat. At. Yadr. **37** (2007) 1477

$\vec{n} \to p\, e \tilde{\nu}$ or triple nuclear fussion

$$W_{if} \sim X \mathbf{s_n}[\mathbf{k}_n \times \mathbf{k}_\nu] + R \mathbf{s}_n [\mathbf{k}_n \times \mathbf{s}_e]$$

i) FSI with Coulomb

ii) Not all T-odd correlations are related to the true T-invariance violation

- Total cross section of the nA interaction from forward nA scattering amplitude

$$f = \underbrace{A + p_n p_T B(\mathbf{s}\cdot\mathbf{I})}_{strong} + \underbrace{p_n C(\mathbf{s}\cdot\mathbf{k})}_{PV} + \underbrace{p_n p_T D(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TVPV} + \underbrace{p_T E(\mathbf{k}\cdot\mathbf{I})}_{PV} + \underbrace{p_n p_T F(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])}_{TVPC}$$

T-odd correlations in forward elastic scattering (=in total cross section):

Three-fold $(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPV

five-fold $(\mathbf{k}\cdot\mathbf{I})(\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}])$ – TVPC

TRANSMISSION experiment!